Extrasolar Planet Detection Through Analysis of K-Giant Radial Velocity Data

A Senior Project

presented to

the Faculty of the Physics Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science, Physics

by

Floyd D. Linayao

May 2010

Abstract

Extrasolar planet detection is an ongoing and growing field of scientific research. To date, there are over 400 planet candidates discovered by various means of detection. Currently, astronomers taking observations at Lick Observatory are searching for potential extrasolar planets around K-giant stars. The project was originally developed to monitor stars to be used in the astrometric grid for NASA's Space Interferometry Mission (SIM). While using the radial velocity method to test if the astrometric centers of K-giants were stable, astronomers came to the realization that the same process could be used for extrasolar planet detection. Of the 373 K-giants being observed at Lick Observatory, using the Coude Auxiliary Telescope (CAT), several stars show promising signs of extrasolar planets with masses larger than Jupiter. Others seem to reveal a pattern in their data, related to planetary motion, but they need more radial velocity data to confirm the existence of a planet. The SIM project originally ruled out binary stars from being useable grid star, due to their large astrometric jitter; nevertheless several have been found to lie among the observed K-giants.

Introduction and Background

It has been long assumed there are planets orbiting stars beyond our solar system. There are, on average, billions of stars in a galaxy and billions of galaxies in the universe. Our own Milky Way contains around 100 billion stars alone. It would be logical to believe our solar system is not unique and there must be other planetary systems beyond our own. The term extrasolar planet refers to any planet beyond our own solar system. To date, there are 429 extrasolar planets candidates[1] found through various techniques, with many more awaiting discovery.

The data analyzed in this paper comes from an ongoing project, which utilizes K-giant stars for their observations. It doesn't have an official name, but for reference purposes it will be referred to as K-giant Planet Discovery (KPD). It came about as an unintended result from another project, The Space Interferometry Mission (SIM). SIM, which is currently under development, is designed to perform astrometry. Astrometry is the branch of astronomy dealing with the precise measurement, on the order of microarcseconds, of celestial bodies, more specifically stars. It should be able to determine the distance and position of stars with extreme accuracy. In order for SIM to work, it needs to make use of an astrometric grid, containing many stars uniformly distributed throughout the sky. This grid is used as a reference frame for SIM's observations. It is important because in order to perform astrometry on this level, your reference frame from which all your observations are based off of, needs stars whose photocenters can be

[1] Based on extrasolar planet data compiled at http://www.exoplanet.eu

accurately determined. (Frink et al., 2001) Among SIM's other capabilities, it should be able to detect Earth like planets orbiting other stars[2].

The grid needs about 1500 to 3000 stars uniformly distributed throughout the sky and they must be brighter than 12th magnitude, to prevent dedicated grid observing time from be too large of a fraction of science observing time. Bright O and B stars would fit these requirements but were ruled out due to some of their properties. Their radial velocities are difficult to measure precisely due to their location in the spiral arms of galaxies and their rotations are too fast. From previous observations of O and B stars, we know that they are not good radial velocity targets because they have very few absorption lines. The most important requirement is astrometric stability of the photocenter must be known to within a few microarcseconds. The reason K-giants were chosen was because they met these particular requirements and there were no other reasonable alternatives. In 1999, a group of astronomers originally working the astrometric grid for SIM began taking radial velocity data on a trial set of 86 K-giants at Lick Observatory. Since then, they've continually added more stars to the list (Frink et al., 2001).

Since the method required to observe the K-giants for the SIM project was the same for performing extrasolar planet detection, the KPD project naturally came to be. Currently the KPD project is no longer associated with SIM and does observations on over 350 K-giants. All of data is collected at Lick Observatory using the Coude Auxiliary Telescope (CAT) and the high resolution spectrometer located there. The project is run and maintained by several astronomers. Throughout the year, they make trips to Lick Observatory and collect approximately six nights of data per month for the stars that are up during their visit. Once data is collected it is sent to UC Berkeley to be reduced and analyzed. From there, they can determine the radial velocity for the night's observation. This project is conducted in collaboration with the California Planet Survey, based out of San Francisco State University and UC Berkeley. Astronomers working on KPD can be found from all over the world. The lead scientists are located in Germany at the Landessternwarte Königstuhl, which is part of the Centre for Astronomy of Heidelberg University.

Radial Velocity Method:

Over a century ago astronomers were aware that Doppler-shift measurements could be utilized to detect extrasolar planets (Marcy & Butler, 2000). However, at the time there was not enough interest in the scientific community and the appropriate technology had not been invented to do such observations. Only recently have astronomers been able to concretely confirm that planets do exist and orbit around stars other than our own.

In the year 2000, Doppler measurements have shown Jupiter-mass objects following Keplerian motion around stars and have helped astronomers find 28 Jupiter-mass planets from a

[2] The SIM website is located at http://sim.jpl.nasa.gov/

survey of 500 main-sequence stars (Marcy & Butler, 2000). As of yet, we do not know the true properties of sub-10M_J objects around other stars. It is something that must be verified by astronomical observations, along with theory. Currently, Doppler searches can detect planets with masses as low as 0.01 M_J (1% mass of Jupiter) and orbits ranging between 0.01 AU to 5.8 AU from its parent star[3].

Previous methods of measuring radial velocity of star had a minimum uncertainty of ~1 km/s. Jupiter affects the radial velocity of the Sun by 0.0124 km/s. A better technique had to be developed if astronomers were to detect Jupiter-mass extrasolar planets. (Butler et al., 1996)

There are several different techniques that have been employed to detect extrasolar planets. The data analyzed in this paper makes use of the Radial Velocity Method. It exploits the fact that a star wobbles due to the mutual gravitational force of the planet(s) orbiting it. This wobble causes a Doppler shift in the light spectrum of the star, which can be measured using an absorption reference cell.

To help explain how we use the Radial Velocity Method to detect extrasolar planets, I will employ Newton's 2nd and 3rd laws of motion.

2nd: F = ma
3rd: For every action there is an equal and opposite reaction

When a planet is orbiting its parent star, it feels a gravitational force from the star. The star feels the same gravitational force from the planet (3rd law). However, seeing that the forces are equal and the masses between the star and planet are vastly different, this causes two bodies experience vastly different accelerations. The planet is less massive, thus it has the greater acceleration (2nd law). Additionally, it is often stated that the planet orbits the star, while the star remains stationary; this is not true. Although it seems that the planet is orbiting the star, both the planet and the star are orbiting their common center of mass -- it just so happens that the center of mass is within the star and the star's orbit is very small around this center. This in effect makes the star wobble when an orbiting planet(s) is present.

Austrian physicist Christian Doppler observed the phenomenon that the frequency of sound changes if either the source or receiver is put into motion (Taylor et al., 2003). It has since been called the Doppler effect. There is also a version of the Doppler effect pertaining to light. Light moving towards an observer is shifted towards shorter wavelengths and light moving away towards longer wavelengths. If we take the Earth to be stationary, then the star's wobble would create Doppler shifts of the star's light spectrum.

In order to measure the Doppler shift of the star's spectrum, we need to compare it to a reference spectrum. We must use a reference spectrum because the wavelength shift of the star's

[3] Based on radial velocity data compiled at http://www.exoplanet.eu

spectrum caused by the orbiting planet(s) is very small. Without a reference spectrum, one would not be able to tell the wavelengths have even shifted because of the minute changes in local conditions. The location of the absorption lines is affected more by the bouncing light about the telescope and passage through a spectrograph than the stellar motion itself. But if we use a reference spectrum, the reference absorption lines also undergo the same effects as the stellar absorption lines, so in the end we can account for the minute changes and we can determine how far the stellar absorption lines have shifted due to stellar motion alone.

Every chemical element has a unique absorption and emission spectrum. Stars are mostly made of hydrogen and helium and their spectral lines are easily identified. The star's spectrum will shift to shorter and longer wavelengths as it wobbles towards and away from us. If we pass the star's spectrum through a reference absorption cell we are able to compare the star's Doppler shifted spectrum to stationary reference spectrum and determine the radial velocity of the star. In our case, we use iodine's spectrum for reference because Lick Observatory uses an iodine absorption cell. The reason they chose iodine over other elements/molecules is because they wanted a non-lethal stable substance that provided sharp features over the 4000 to 6000 Å, the range over which a majority of stellar radial velocity information resides. Different substances had different advantages but molecular iodine was the best overall compromise. (Butler et al., 1996)

There are several sources of error that come into play when using the iodine cell technique for measuring the radial velocity of stars (Butler et al., 1996).

1. Photon-limited errors
2. Wavelength calibration errors
3. Errors caused by spectrometer PSF
4. CCD inhomogeneities
5. Photospheric turbulence

Overall the total systematic uncertainties in the Doppler technique exist at the 1 m/s level. But the limit to how precise velocity measurements can be is determined by the star itself. (Butler et al., 1996)

<u>Requirements to be a planet:</u>

1. Object must be orbiting a star
2. Object must be spherical
3. Object must have cleared its orbit

These requirements are sometimes phrased in different ways, but nonetheless they all basically state the same thing. The first is necessary to rule out moons and free floating objects in space that have no affiliation with a particular star or solar system. The second is essentially a size requirement. When objects are massive enough, they tend to form into a sphere, due to gravity. The third says there cannot be a lot of other space debris within the same orbital path. The planet must be the major object within that orbit. This is one of the reasons why Pluto is no longer considered a planet. Unfortunately, these requirements don't put an upper limit to the mass of the planets. Technically speaking, brown dwarfs and binary stars also meet the requirements. Since the masses of brown dwarfs range between that of planets and stars, we need to set a mass limit to distinguish them from planets. Brown dwarfs have a typically have a minimum mass of $75M_J$. For the purposes of this paper we will set this as the upper limit for a planet's mass.

<u>Observed properties of extrasolar planets</u> (Marcy & Butler, 2000):

1. Planets typically form with masses below $7M_J$, although greater masses are not unheard of.
2. Their host stars have higher abundances of heavy elements than field stars.
3. Orbits larger than 0.2 AU tend to have eccentricities greater than 0.1

Analysis

<u>The Console:</u>

The program used to analyze the radial velocity data is called the Systemic Console. It is a Java-based program that uses various, orbital parameters to try and fit a planetary orbit to the data. The following section does not go into detail about how to use the Console. It will only provide a brief overview of how the Console works. There are tutorials on their website (http://oklo.org). The following version 1.0.98 RC is described below.

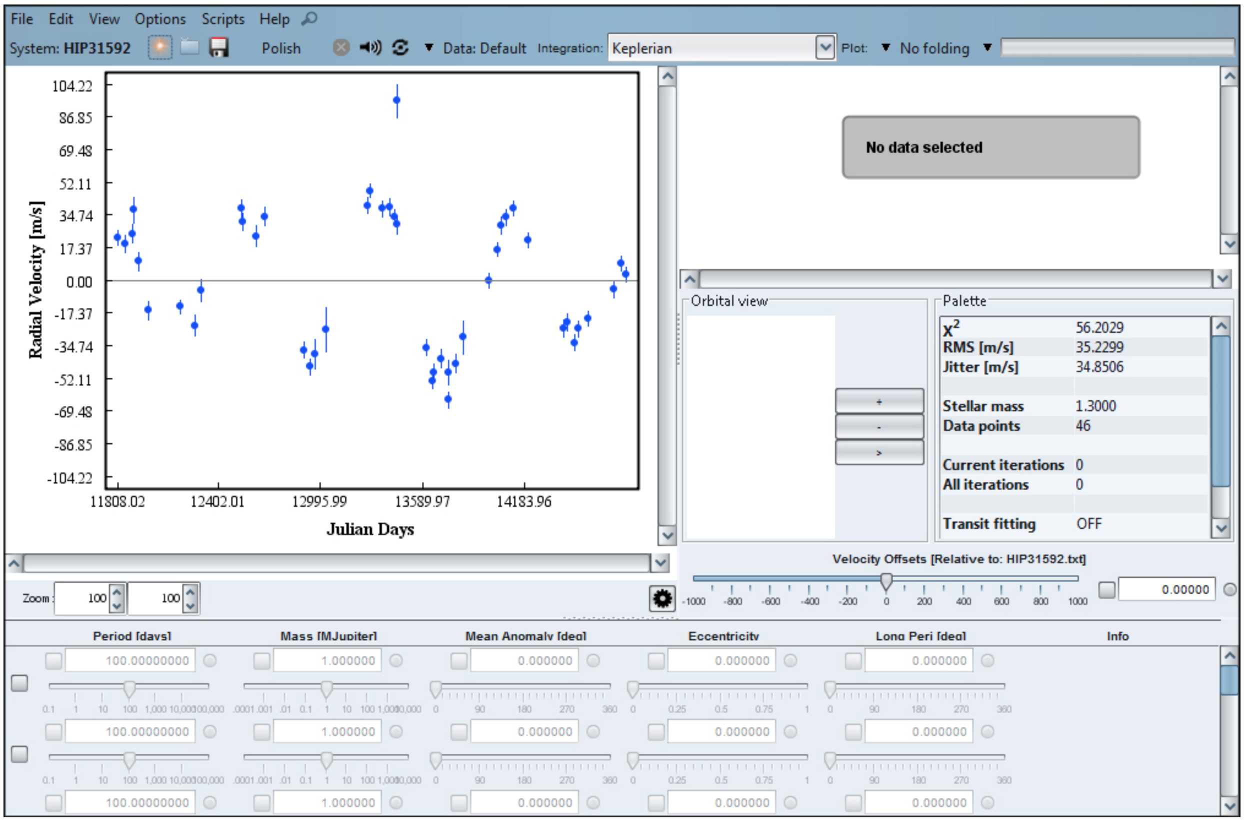

Figure 1. Console Overview

This is the basic interface of the Console. Once the data is loaded, it is displayed in the box on the left. For this example I am using the star HIP31592. Without doing any analysis of the data, one can already see there is a slight oscillating pattern in the data. There are six different orbital parameters that can be adjusted: period, mass, mean anomaly, eccentricity, longitudinal period, and the velocity offset. There is a section for orbital view, which allows the user to see what the orbit of the potential planet(s) would look like according to the parameters set.

The loaded data comes from the radial velocity measurements of a particular star. The data is contained in a text file, which lists the radial velocities of the star taken at different Julian dates. The following is a portion of the data set for the star HIP31592 as it appears in the text file.

```
11808.021      22.5266      4.04234
11853.990      19.2722      4.38784
11896.855      24.7050      5.09227
11901.860      37.2784      6.89085
11929.723      9.93433      4.77322
```

The first column of numbers is reduced Julian date at the time of the observation. The second column is the radial velocity measured in m/s. The third column is the uncertainty measured in m/s.

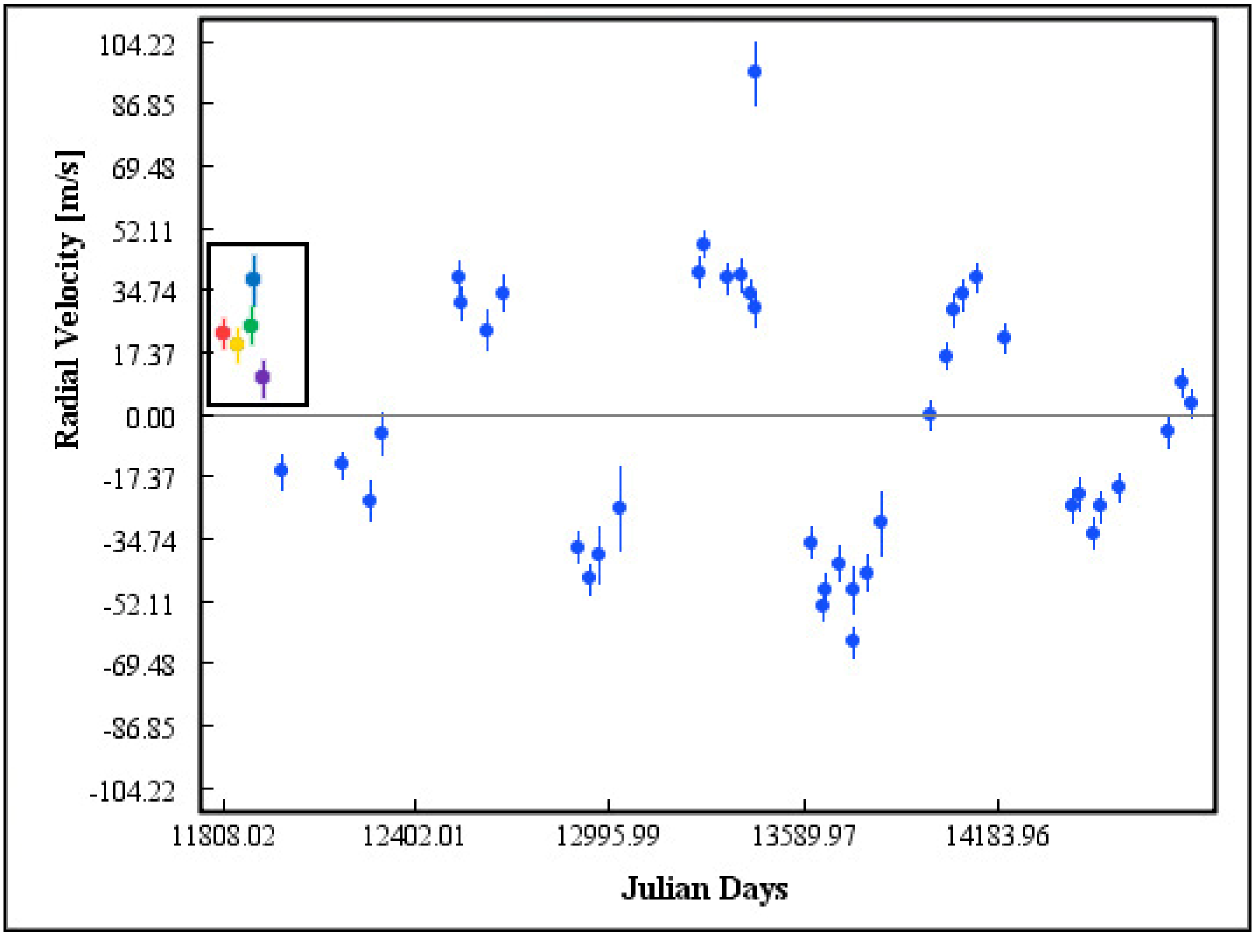

Figure 2. Data Loaded in Console

When the data is loaded into the Console, it is displayed as a series of points plotted by Radial Velocity vs. Julian Date. For instructional purposes, the sample data above has been boxed off and color coded to show how it becomes displayed in the Console.

The first parameter to be adjusted is the period, measured in days. Once a period is set, a curve appears on the data. The longer the period the wider the curve will be, and vice versa.

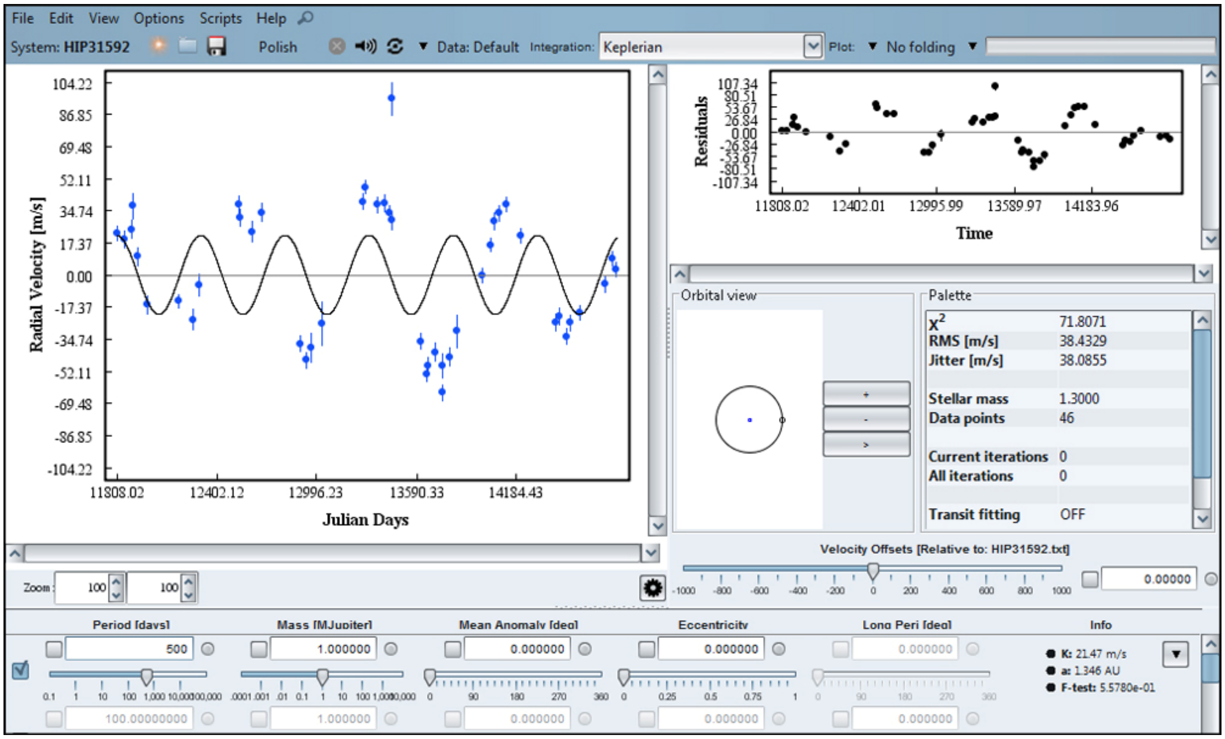

Figure 3. Adjusting Orbital Period (500 days)

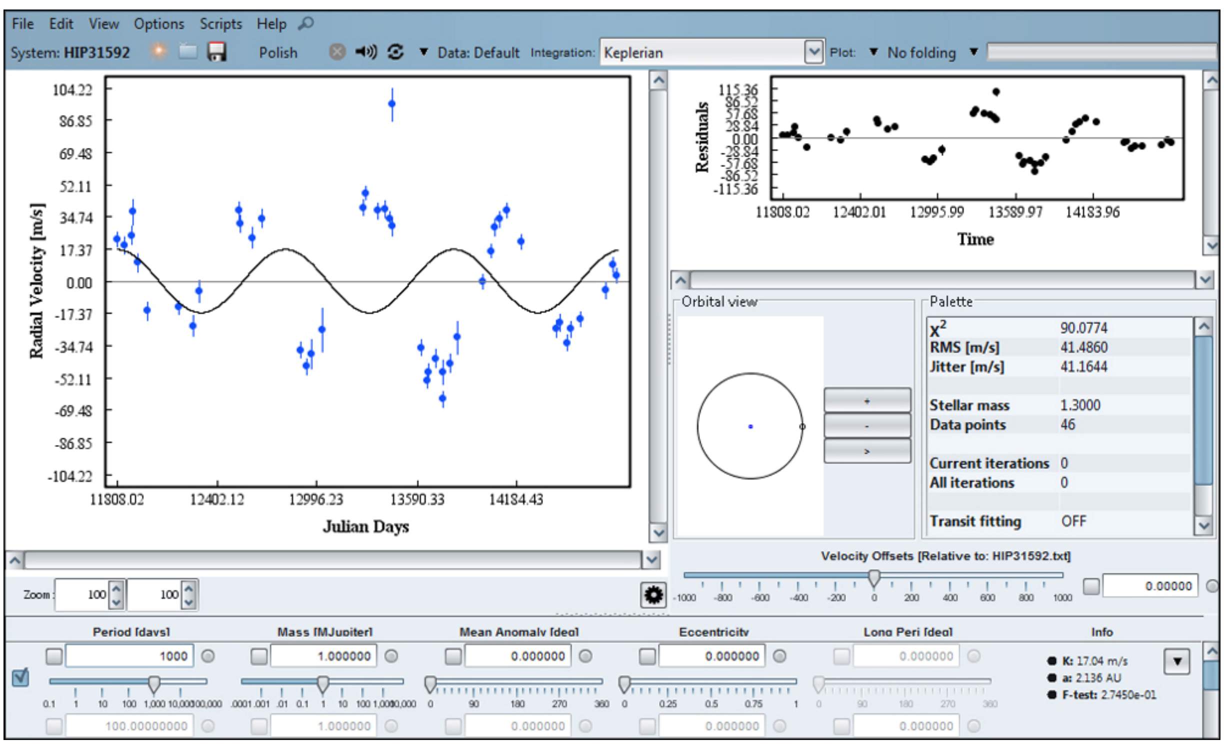

Figure 4. Adjusting Orbital Period (1000 days)

As you can see, the curve for a 1000 day period is wider than the 500 day period. It may be difficult to tell but the orbit in the orbital view window is slightly larger for the 1000 day period.

Adjusting the mass slider will affect the amplitude of the curve. Here, the setting refers to a multiplicative factor of Jupiter's mass. A reading of 3.0 means the potential planet is 3 times more massive than Jupiter.

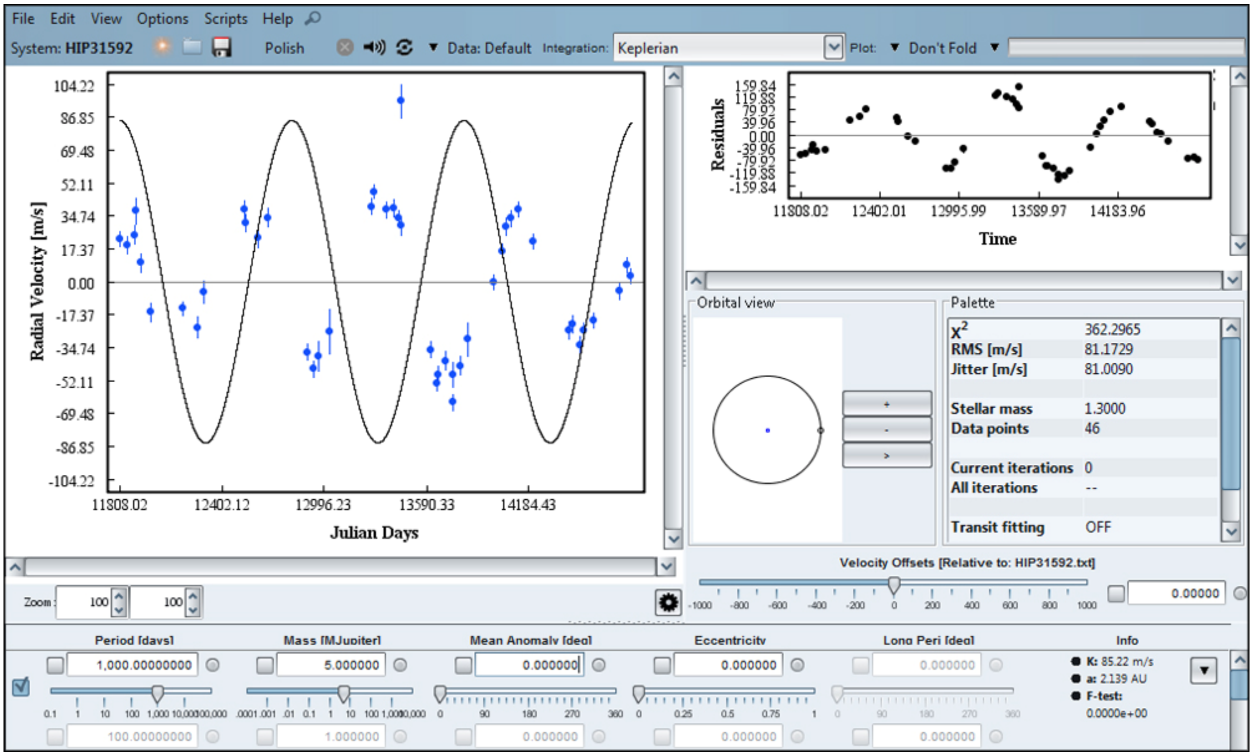

Figure 5. Adjusting Mass

Increasing the mass to 5 times that of Jupiter's shows an obvious increase in amplitude.

The mean anomaly slider is used to shift the curve left and right. This refers to where the planet is in its orbit. The slider settings range from 0 to 360.

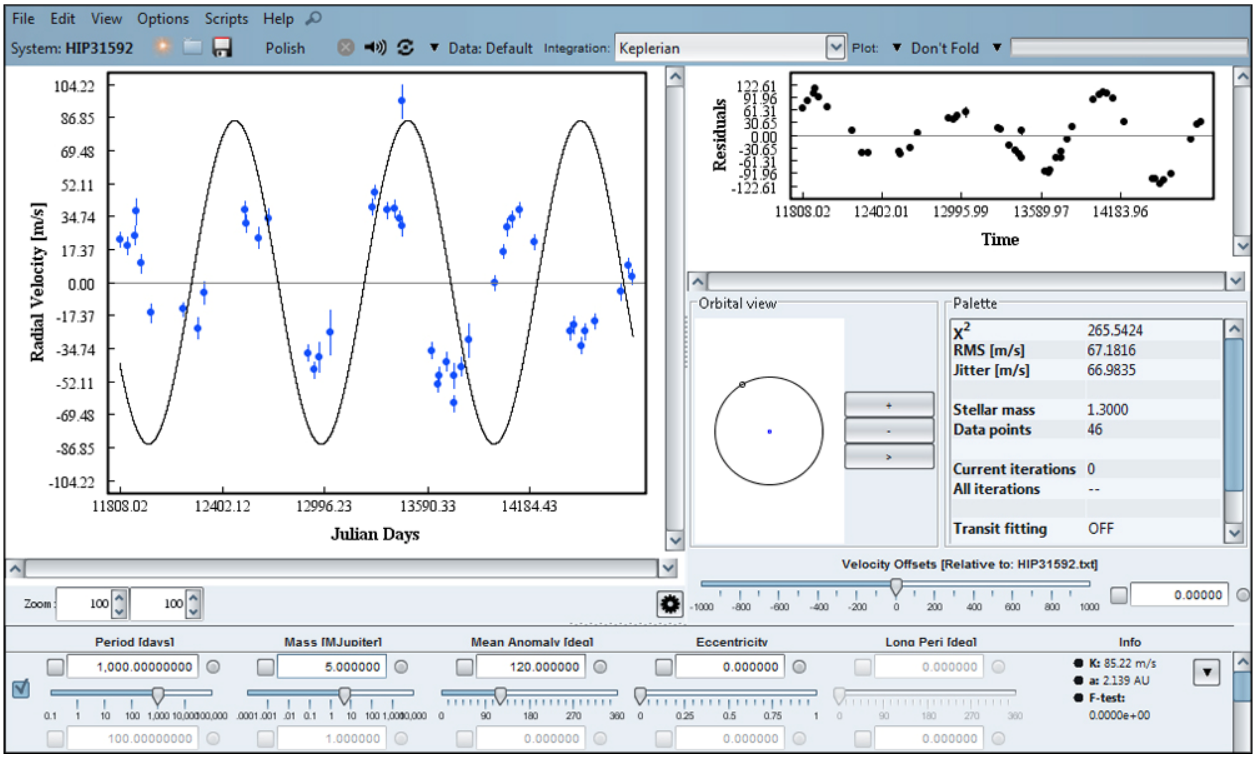

Figure 6. Adjusting Mean Anomaly

When we set the mean anomaly to 120^{o} the planet moves 120^{o} counterclockwise in its orbit. The curve also shifts to the left relative to the data. The actual amount it shifts over is 1/3 of a period because 120^{o} is a third of 360^{o}.

The eccentricity slider adjusts the eccentricity of the planet's orbit. An eccentricity of 0 means the planet has a perfectly circular orbit and an eccentricity of 1 means the planet is not in orbit anymore.

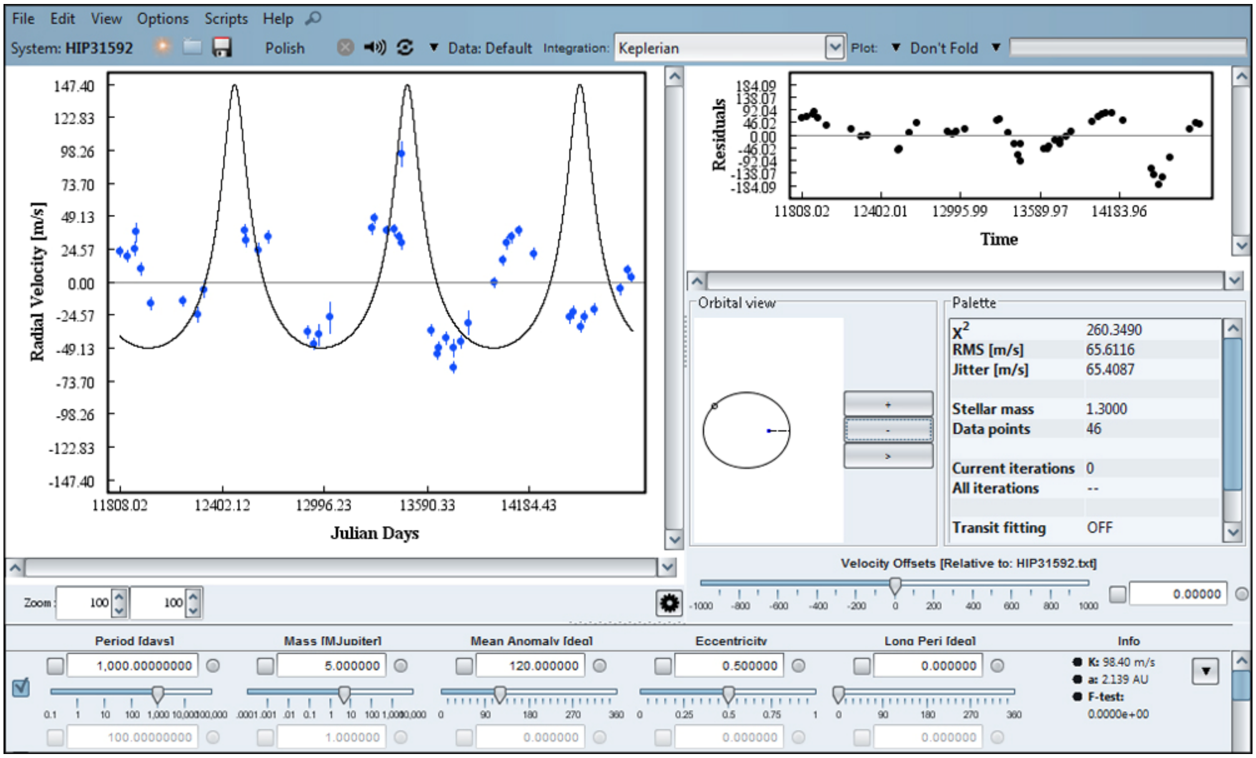

Figure 7. Adjusting Eccentricity

Setting the eccentricity to 0.5 makes the orbit more elliptical rather than circular. You can also see how this affects the curve. The peaks become more pointed while the troughs become more rounded. This is because a planet travels faster when it is on its closest approach to the star and slower when it is further away. So the peaks are more pointed because the planet is changing direction in its orbit much faster when it is close to the star.

The longitudinal period slider adjusts the orientation of the planet's elliptical orbit around the star. It works similar to the mean anomaly slider in that it can rotate the orbit 360^{o}. It is measured with respect to the line of sight of Earth. If we were to draw a line between the Earth to the star and a line between the star to its periastron (point of closest approach between the star and planet), the longitudinal period is the angle between these two lines.

Sometimes we are seeing the plane of the planet(s) at a tilt. It is impossible for astronomers to determine the inclination angle of the planets' orbital plane. Stars are so far away that they always appear as points of light. They are so bright and so large compared to the planets that we cannot see the plane the planets are orbiting in (assuming all planets are orbiting in the same plane). All we can measure is the relative wobble between the host star and the planets using the radial velocity method. This affects our ability to accurately measure the mass of a star. If we were to know that we are looking at the plane of a planetary orbit edge on then the mass of the star can be accurately determined because we would be able to measure full effect the planets have on the star. As the plane begins to tilt, the effects become less apparent. If the plane were tilted a full 90^{o} to our line of sight (top or bottom view), then we would have no information about the mass of the star. In order to measure the mass, we need to measure the Doppler shift of the stellar spectrum. If the orbit were tilted 90^{o} then the star would be wobbling in a plane perpendicular to the one we need to measure and thus no Doppler information can be obtained because the technique relies on the towards and away motion of the star. This leads us to assigning a minimum mass to the parent star since we don't know the tilt of the orbit. A tilt of 0^{o} (edge on) would give us the maximum, true mass of the star.

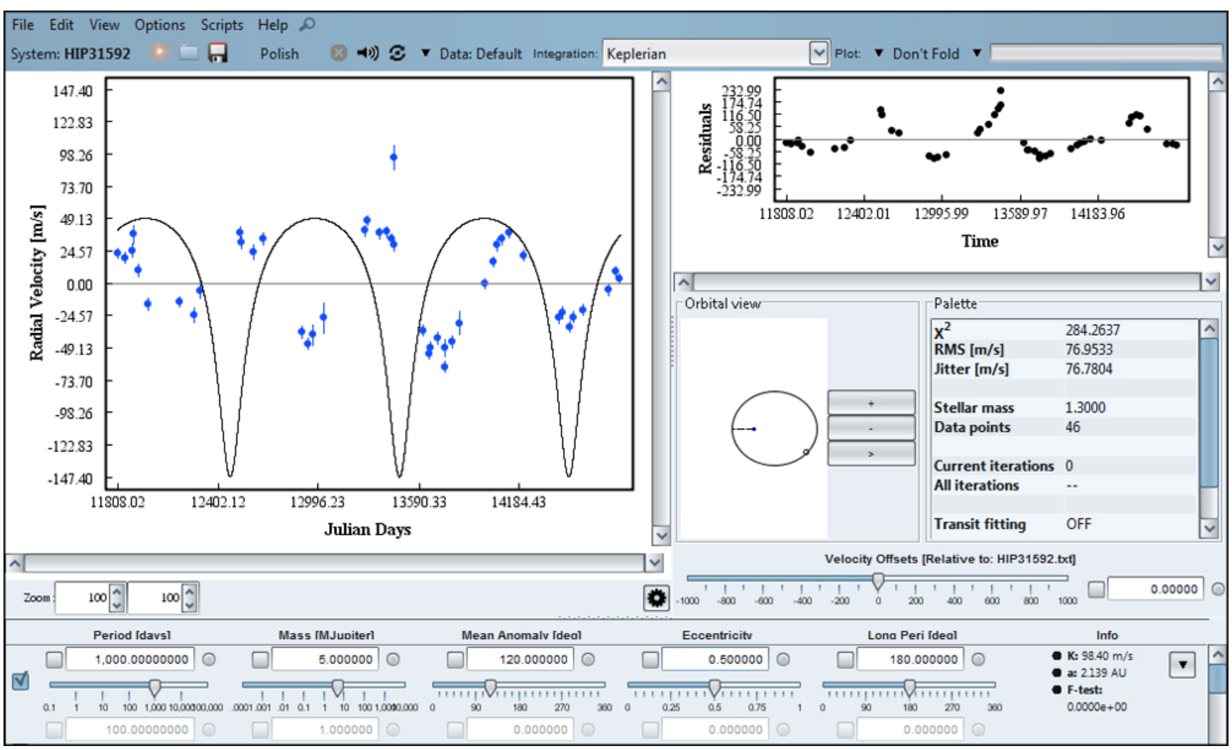

Figure 8. Adjusting Longitudinal Period

Setting the longitudinal period to 180°, you can see that the curve essentially becomes inverted. The orbital view shows that the orbit has rotated and now the point of closest approach (perihelion) is to the left of the star as opposed to the right, as it was before. This is the reason why the curve is flipped.

The last slider is the velocity offset. This adjusts for the relative motion of the star towards or away from Earth, not due to a planet. The motion of the star traveling through space and the motion due to an orbiting planet are two separate entities. This slider is used to counter the effect of the star traveling through space and essentially fixes it in place so that only the motion due to the orbiting planets is detected. In order for the radial velocity method to work we need to set a zero point so that the motion of the star as it travels through space doesn't affect the radial velocity measurements of the star's motion due to an orbiting planet. Moving this slider shifts the data either up or down relative to the curve.

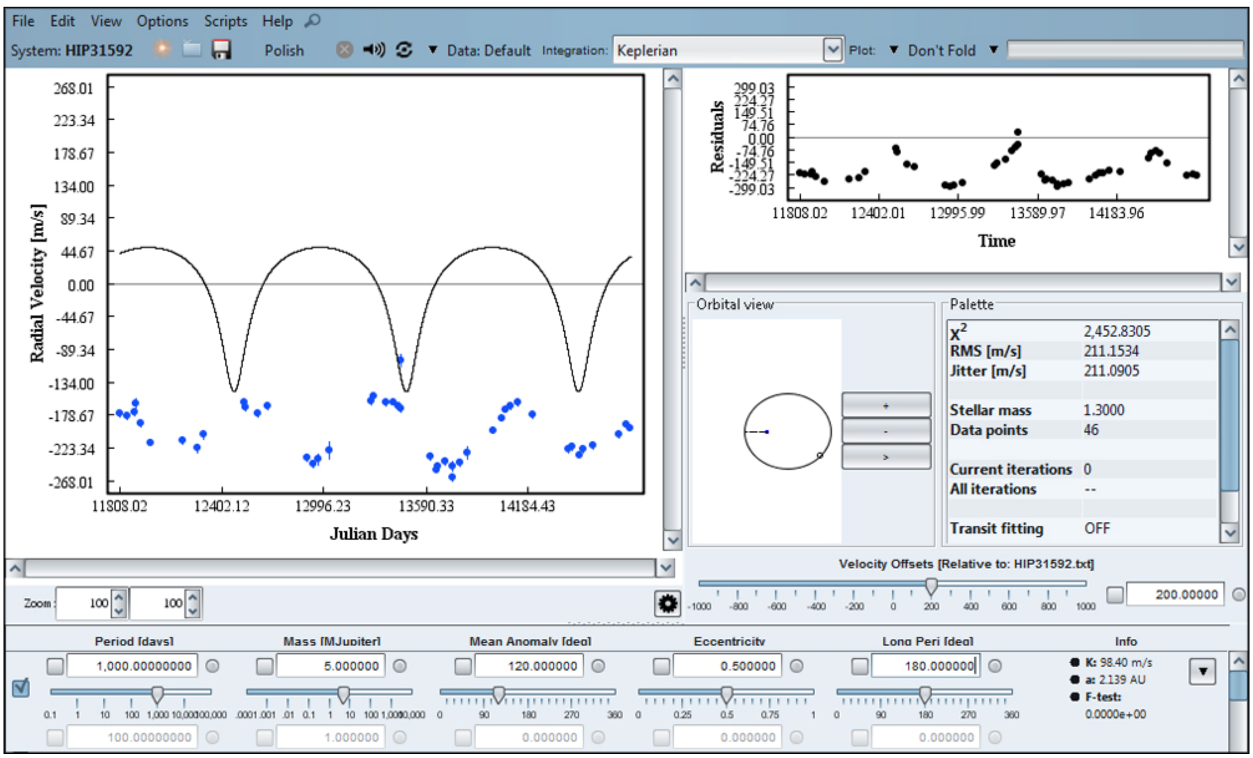

Figure 9. Adjusting Velocity Offset

Setting it to 200 m/s shifts the curve up relative to the data. If it was set to -200 m/s it would shift the curve down.

Keep in mind this was only an explanation as to what the various parameters in the Console adjust, it is by no means a tutorial on how to use it. As you can see from the last figure, the overall fit is not suitable for a planet.

The orbital view window has been referenced a few times. It shows how the orbits of the planet(s) look when the orbital parameters are adjusted. It can show the user how far apart (or close together) two planet's orbits are or if the orbits overlap. It essentially gives the user a visual representation of what it happening with the particular parameters set.

The palette immediately to the right shows some general information about the fit. X^2 is a common statistical test, which tells you how well the curve fits the data. Generally you want it to be as close to one as possible. It also contains other information such as how many data points there are for a particular star and the star's mass, which generally does have an effect on the orbits.

The window above the palette and orbital view window is the residuals window. It shows the user what the data would look like when potential orbits have been subtracted out of the original data. It can be used to help determine if more planets should be added to the fit.

Categories

The radial velocity data for all 373 K-giants was sorted in different categories according to the properties they exhibited when analyzed with the Console. The two main categories were the interesting and uninteresting stars. From there, they were broken down further into subcategories. Sometimes stars fit into more than one category but they were placed into the one with which it showed the most characteristics of.

<u>Interesting Stars:</u>

Planet Candidates:

These are the stars showing the most potential for containing planets. The planetary orbits didn't seem to have any unusual properties that would seem to affect planetary evolution on long time scales. Unusual properties would be anything that places orbital parameters near their limits. For example, having a eccentricity of 0 (perfectly circular orbit), masses that are too big (near the brown dwarf limit), or periods that are too short (less than a day). This could also go in the other direction; high eccentricity, very low mass, extremely long period.

Binary Stars:

A binary star is a system where two stars orbit around their common center of mass, as opposed to a star and planet. It becomes apparent that a star is in a binary system when the orbital parameters give the potential planet a mass several hundred times that of Jupiter and the orbital period is long. Having a long period doesn't immediately raise flags though. Uranus has an 84 year period, but having a high mass well beyond the limit for planets is a give away.

Impossible Orbit(s):

Sometimes the data showed a fit that correlated very well to the data with several planets, but the orbits could not exist. Generally orbits in this category would intersect at many points or come into contact, which cannot be stable in the long term. On rare occasions, two or more planets would be in nearly the same orbit.

Few Data Points:

There seems to be some sort of pattern in the data but the lack of data points makes it difficult to state if there is a planetary system.

Other Interesting:

These fits comprised in this category seem to have some overall correlation to the data, but have several orbital parameters that seem questionable. For example, the planet may have a very high eccentricity or a mass that is approaching the brown dwarf limit. The eccentricity of multiple planets causes orbits to be near each other at certain points, but not intersecting.

Uninteresting Stars:

Short Period(s):

The stars observed in this paper are giant stars. Planets having a short period, on the order of a few days, seem rather peculiar. The planets would have to be within the star to complete an orbit in such a short amount of time.

Other Uninteresting:

The fits for this category didn't correlate well to the data, even though the data sometimes seemed to have a general pattern. Usually there are too many data points not on the fit itself or in order to make the fit work the planets are given strange properties (high mass, very eccentric, short period, etc…). Sometimes there are few data points and the fit relies on large error bars to work. Data points seem to be randomly scattered and the Console can't make a decent fit. In this category, the Console is desperately trying to make a fit, even though there probably isn't anything there.

The Fits

There were two sets of data for this project. The major difference between them, aside from containing different stars, was that the masses of the stars in the first set were known (Mitchell 2004) but not in the second set. For the second data set, all the stars were set to 1 stellar mass for consistency. The only way this affects the results for the second data set would be that the planet masses would be larger. All other orbital parameters should remain the same. All planet candidates and a representative sample of the other categories are featured below. A full list of the stars, the data set they are from, and their categorical type are found in Appendix A.

<u>Planet Candidates:</u>

HIP 20889:

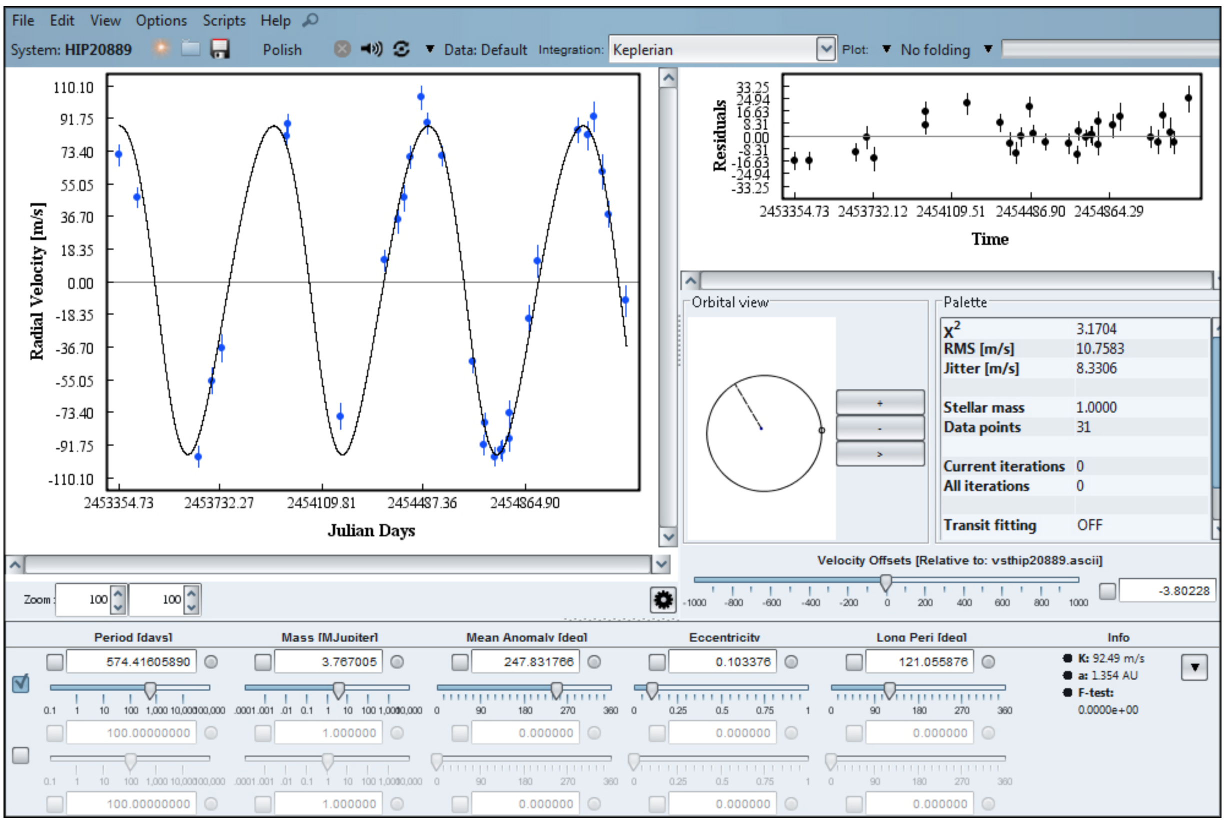

Figure 10. HIP 20889 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
3.1704	10.7583	8.3306	1.0000	31

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	574.41605890	3.767005	247.831766	0.103376	121.055876	-3.80228

HIP 34693:

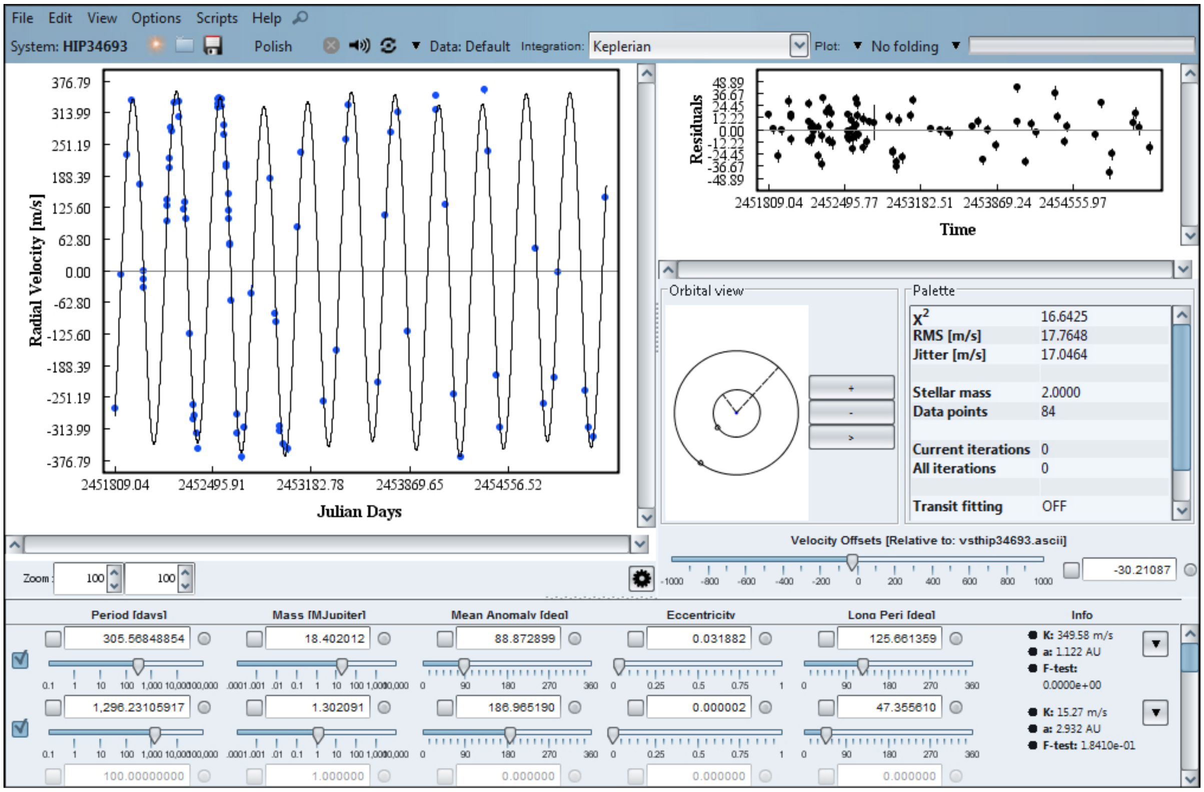

Figure 11. HIP 34693 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
16.6425	17.7648	17.0464	2.0000	84

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	305.56848854	18.402012	88.872899	0.031882	125.661359	-30.21087
2	1,296.23105917	1.302091	186.965190	0.000002	47.355610	-30.21087

HIP 34987:

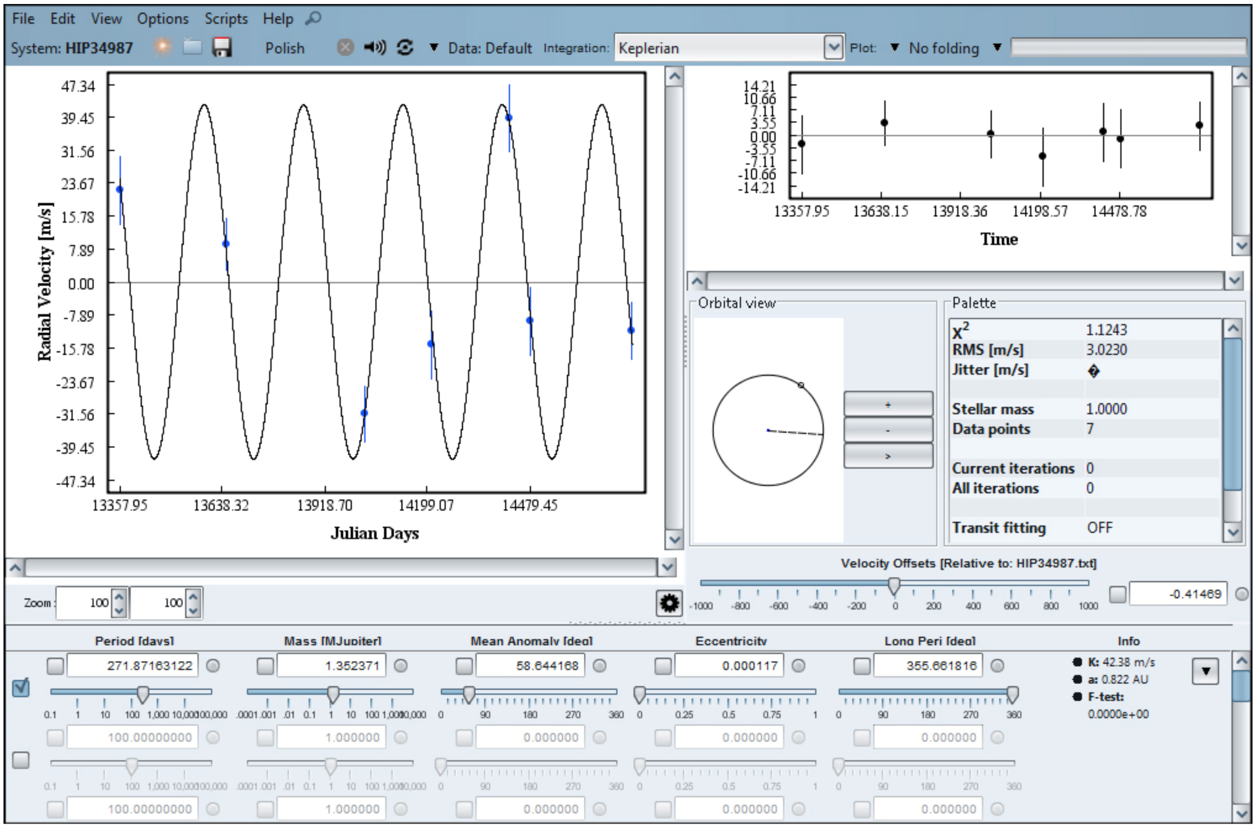

Figure 12. HIP 34987 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
1.1243	3.023	n/a	1.0000	7

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	271.8716312	1.352371	58.644168	0.000117	355.661816	-0.41469

HIP 60202:

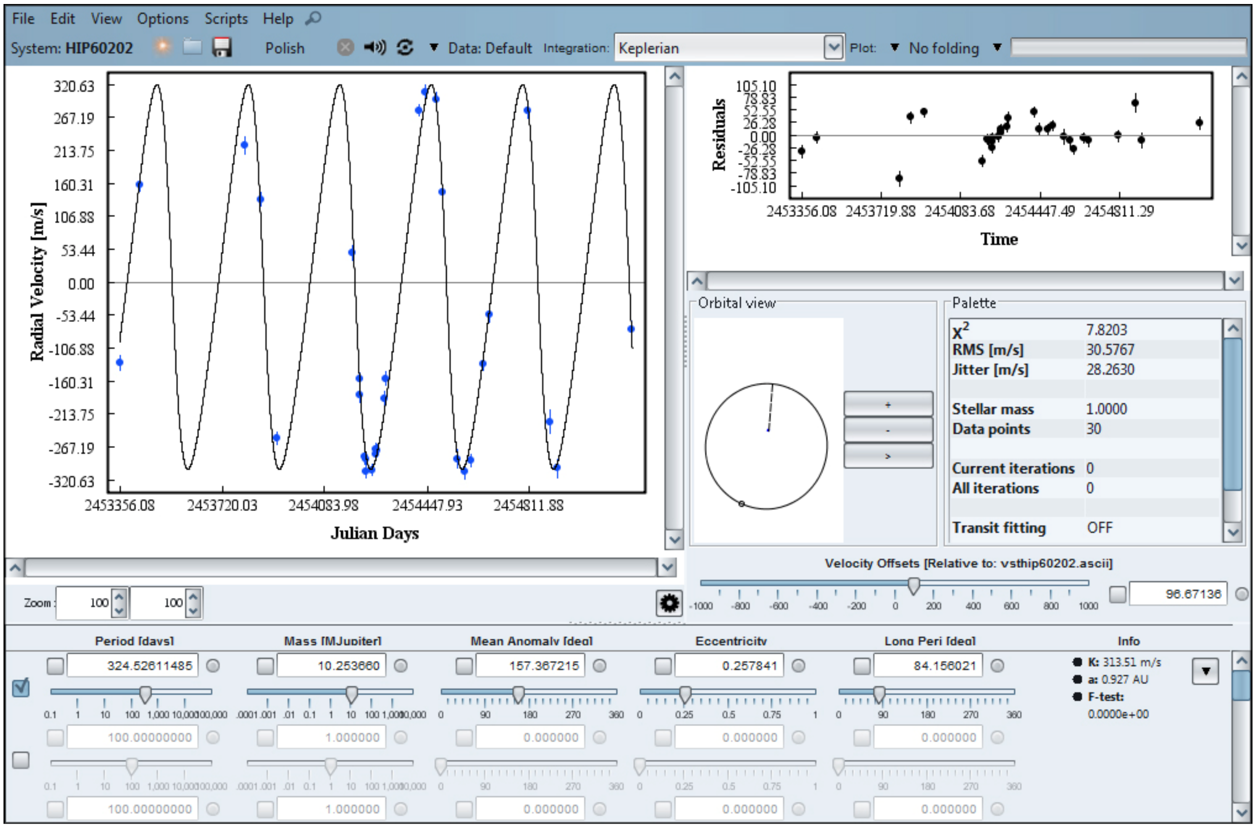

Figure 13. HIP 60202 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
7.8203	30.5767	28.2630	1.0000	30

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	324.52611485	10.253660	157.367215	0.257841	84.156021	96.67136

HIP 88048:

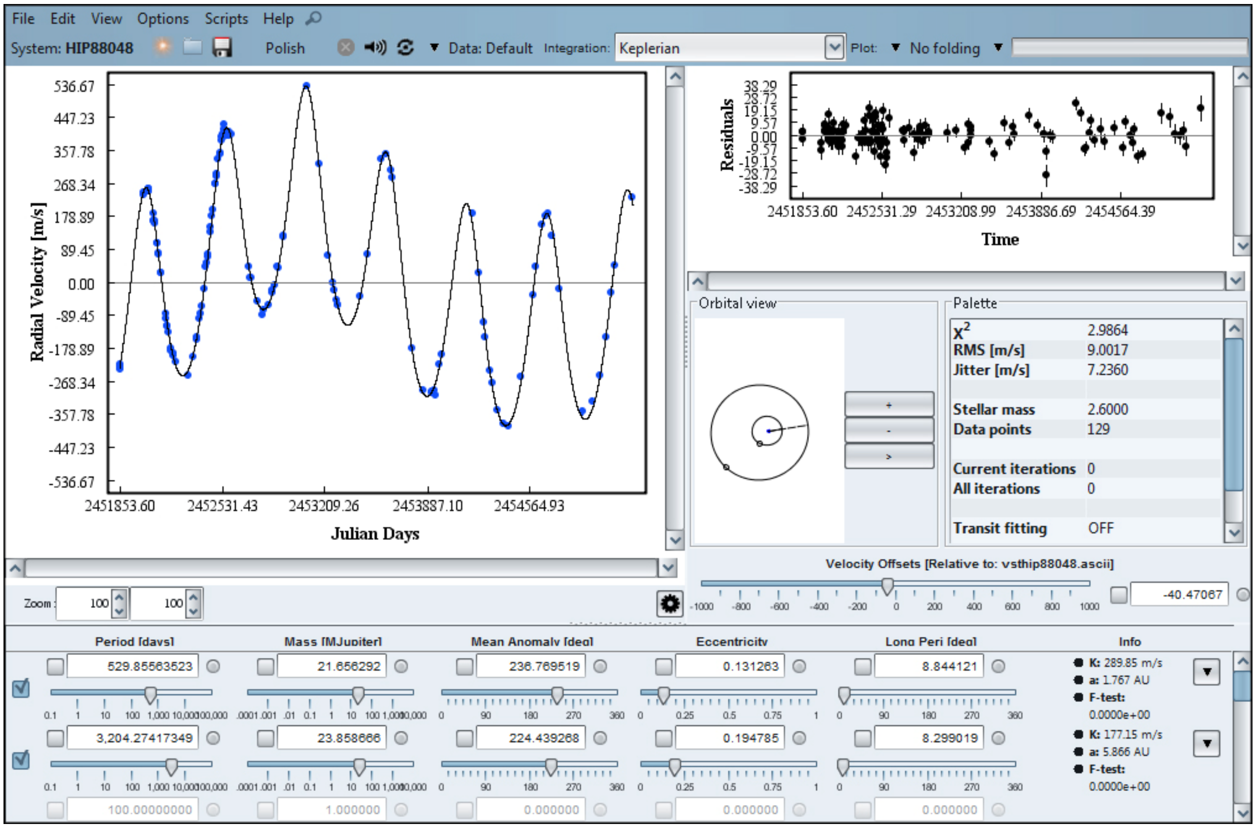

Figure 14. HIP 88048 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
2.9864	9.0017	7.2360	2.600	129

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	529.85563523	21.656292	236.769519	0.131263	8.844121	-40.47067
2	3,204.27417349	23.858666	224.439268	0.194785	8.299019	-40.47067

HIP 114855:

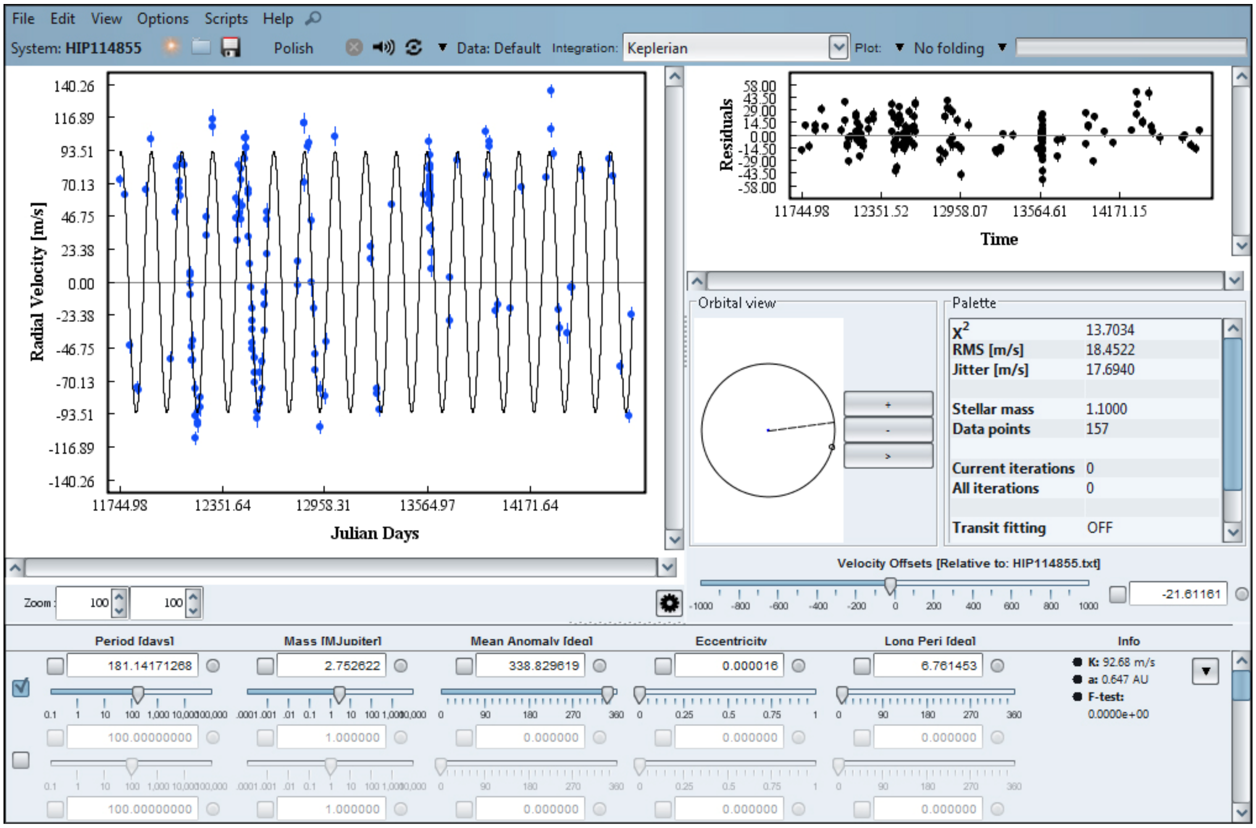

Figure 15. HIP 114855 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
13.7034	18.4522	17.6940	1.1000	157

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	181.14171268	2.752622	338.829619	0.000016	6.761453	-21.61161

<u>Binary Stars:</u>

HIP 76425:

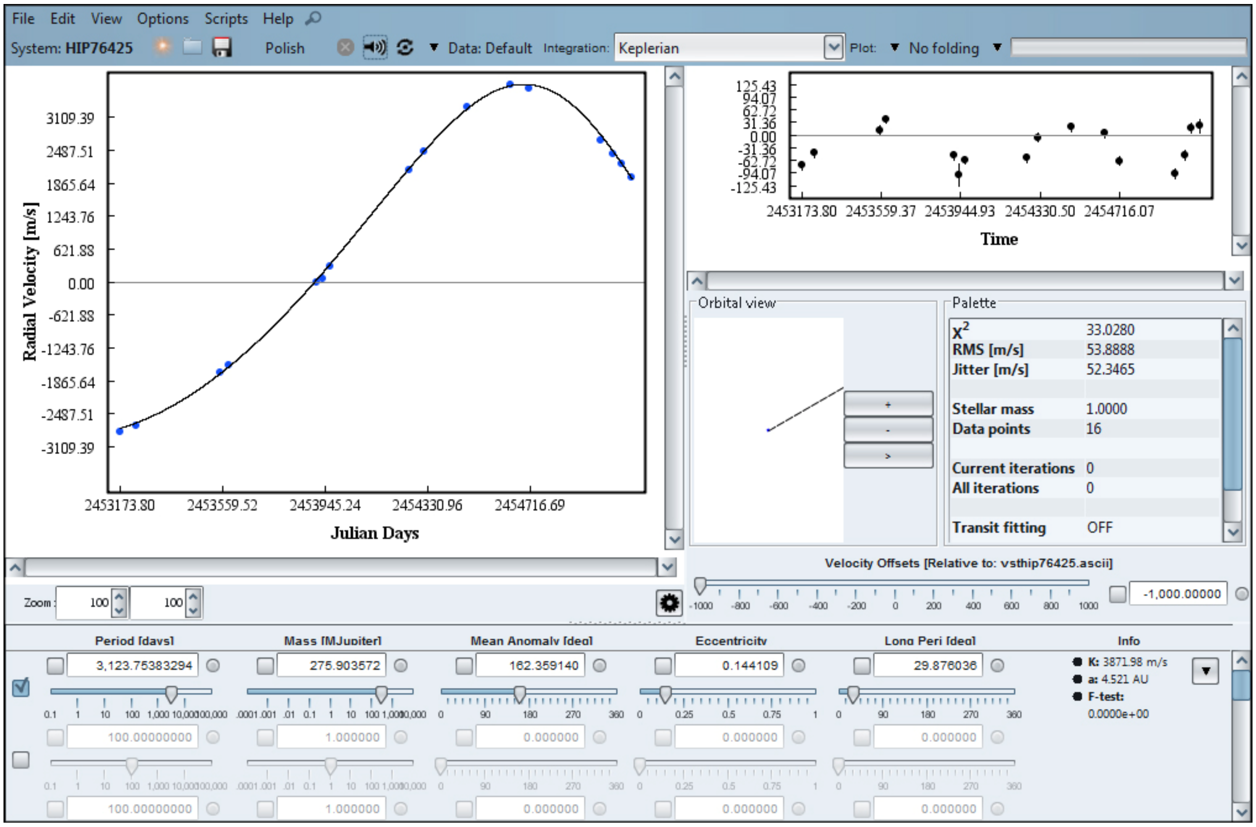

Figure 16. HIP 76425 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
33.0280	53.8888	52.3465	1.0000	16

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	3,123.75383294	275.903572	162.359140	0.144109	29.876036	-1,000.00

HIP 95785:

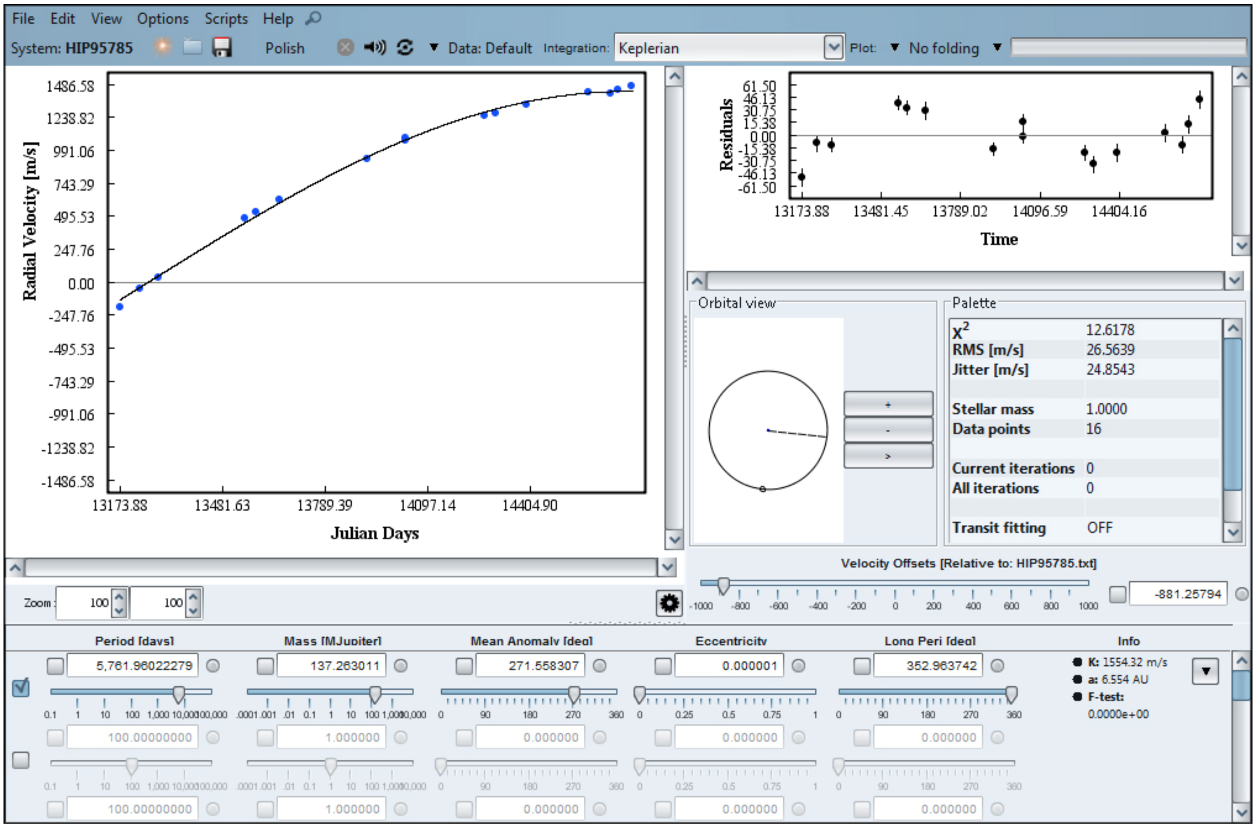

Figure 17. HIP 95785 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
12.6178	26.5639	24.8543	1.0000	16

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	5,761.96022279	137.263011	271.558307	0.000001	352.963742	-881.25794

Few Data Points:

HIP 27629:

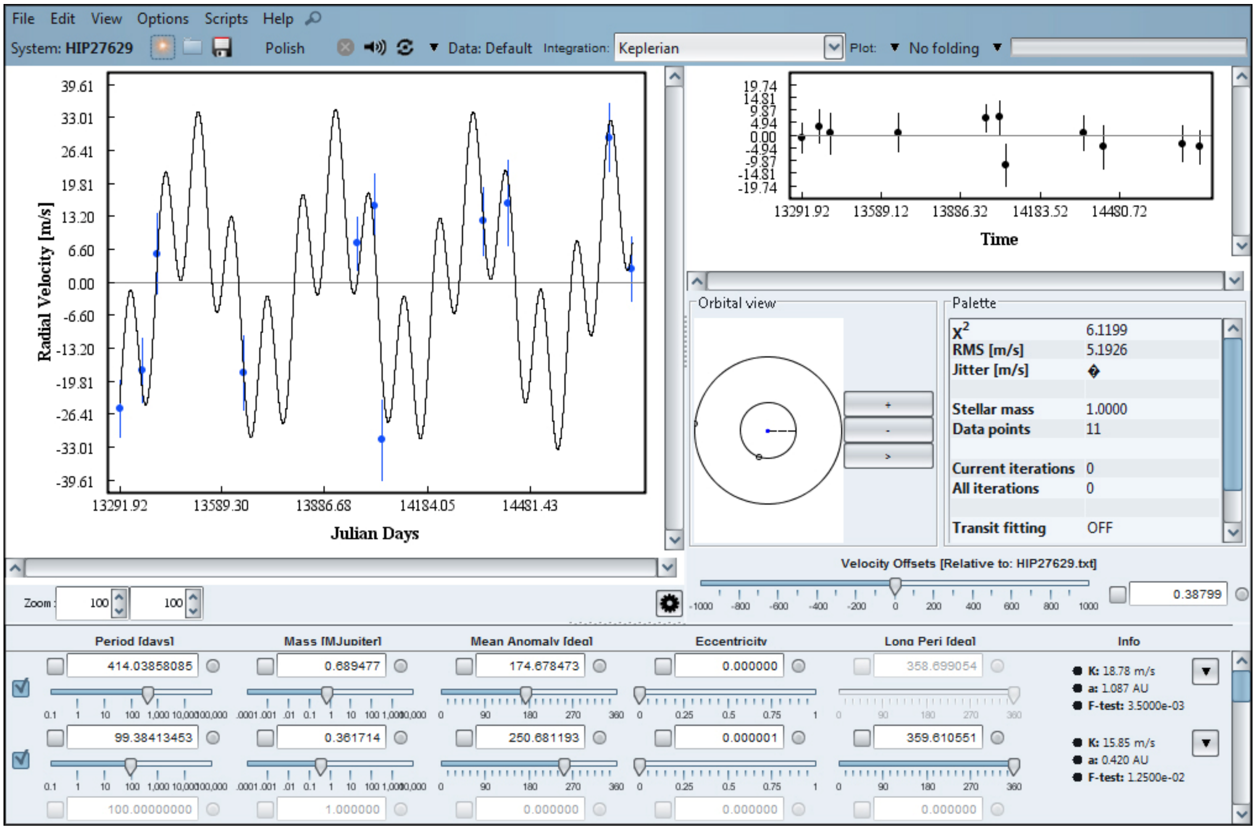

Figure 18. HIP 27629 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
6.1199	5.1926	n/a	1.0000	11

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	414.0385809	0.689477	174.678473	0.000000	n/a	0.38799
2	99.38413453	0.361714	250.681193	0.000001	359.610551	0.38799

HIP 78990:

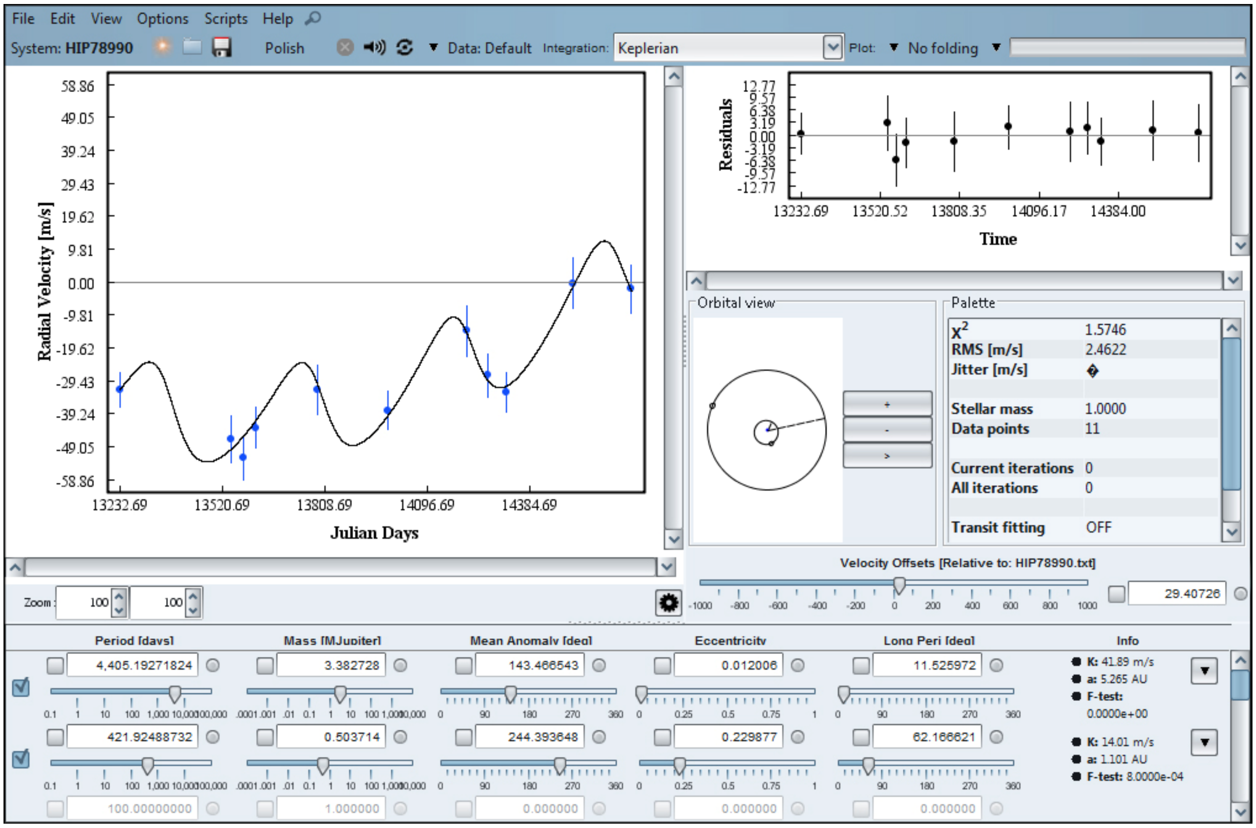

Figure 19. HIP 78990 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
1.5746	2.4622	n/a	1.0000	11

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	4,405.19271824	3.382728	143.466543	0.012006	11.525972	29.40726
2	421.92488732	0.503714	244.393648	0.229877	62.166621	29.40726

Impossible Orbits:

HIP 38253:

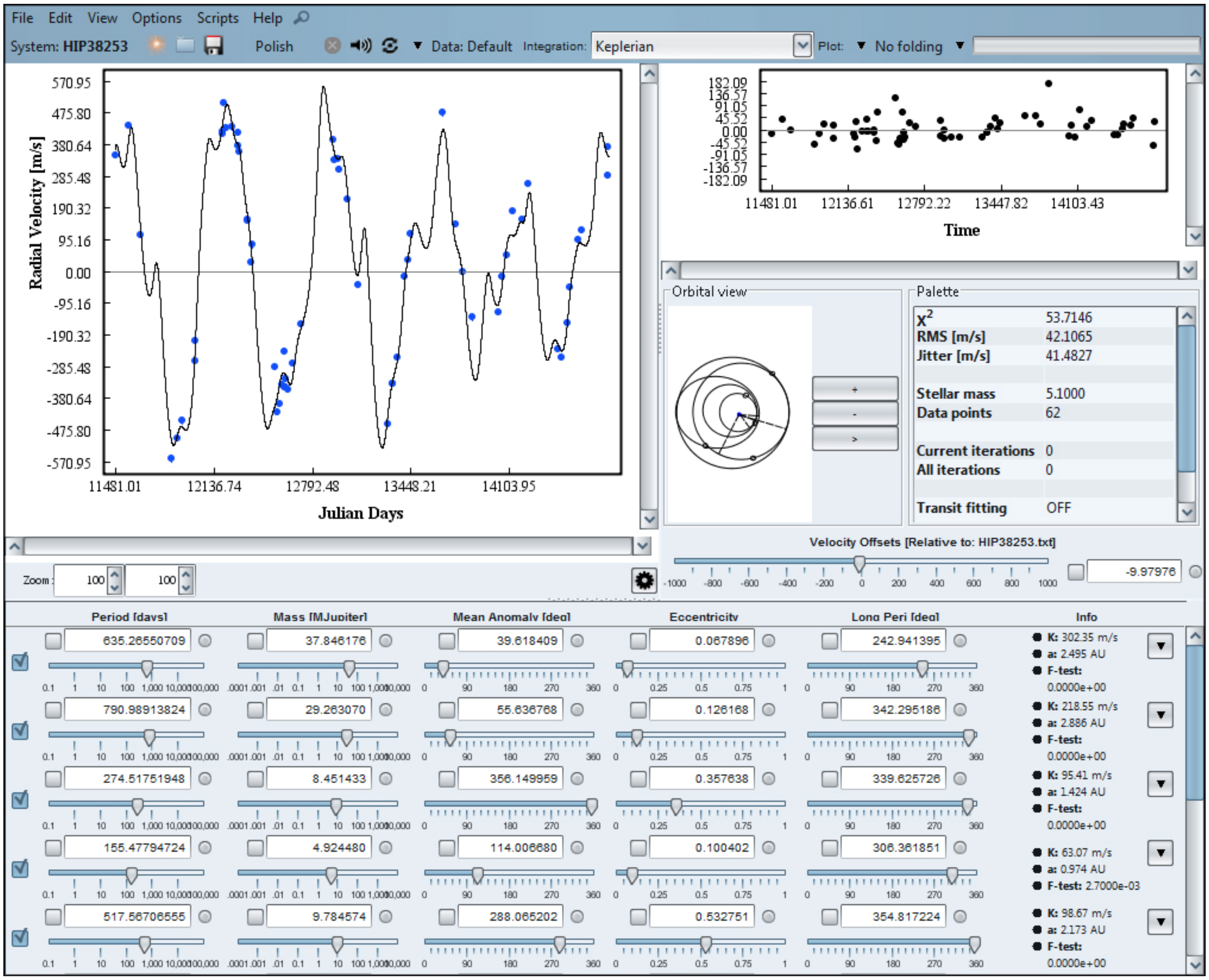

Figure 20. HIP 38253 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
53.7146	42.1065	41.4827	5.1000	62

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	635.26550709	37.846176	39.618409	0.067896	242.941395	-9.97976
2	790.98913824	29.263070	55.636768	0.126168	342.295186	-9.97976
3	274.51751948	8.451433	356.149959	0.357638	339.625726	-9.97976
4	155.47794724	4.924480	114.006680	0.100402	306.361851	-9.97976
5	517.56706555	9.784574	288.065202	0.532751	354.817224	-9.97976

HIP 79195:

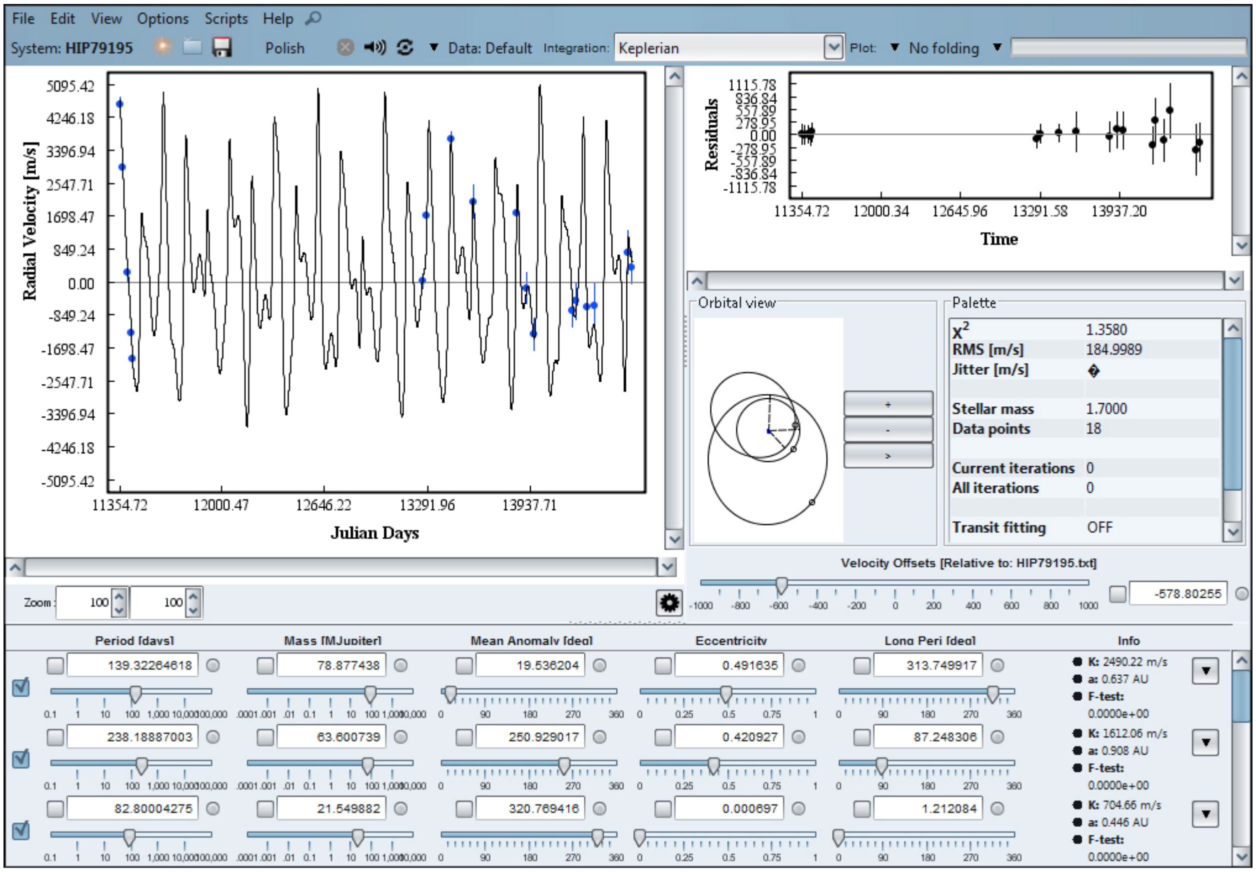

Figure 21. HIP 79195 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
1.3580	184.9989	n/a	1.7000	18

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	139.32264618	78.877438	19.536204	0.491635	313.749917	-578.80255
2	238.18887003	63.600739	250.929017	0.420927	87.248306	-578.80255
3	82.80004275	21.549882	320.769416	0.000697	1.212084	-578.80255

Other Interesting:

HIP 54539:

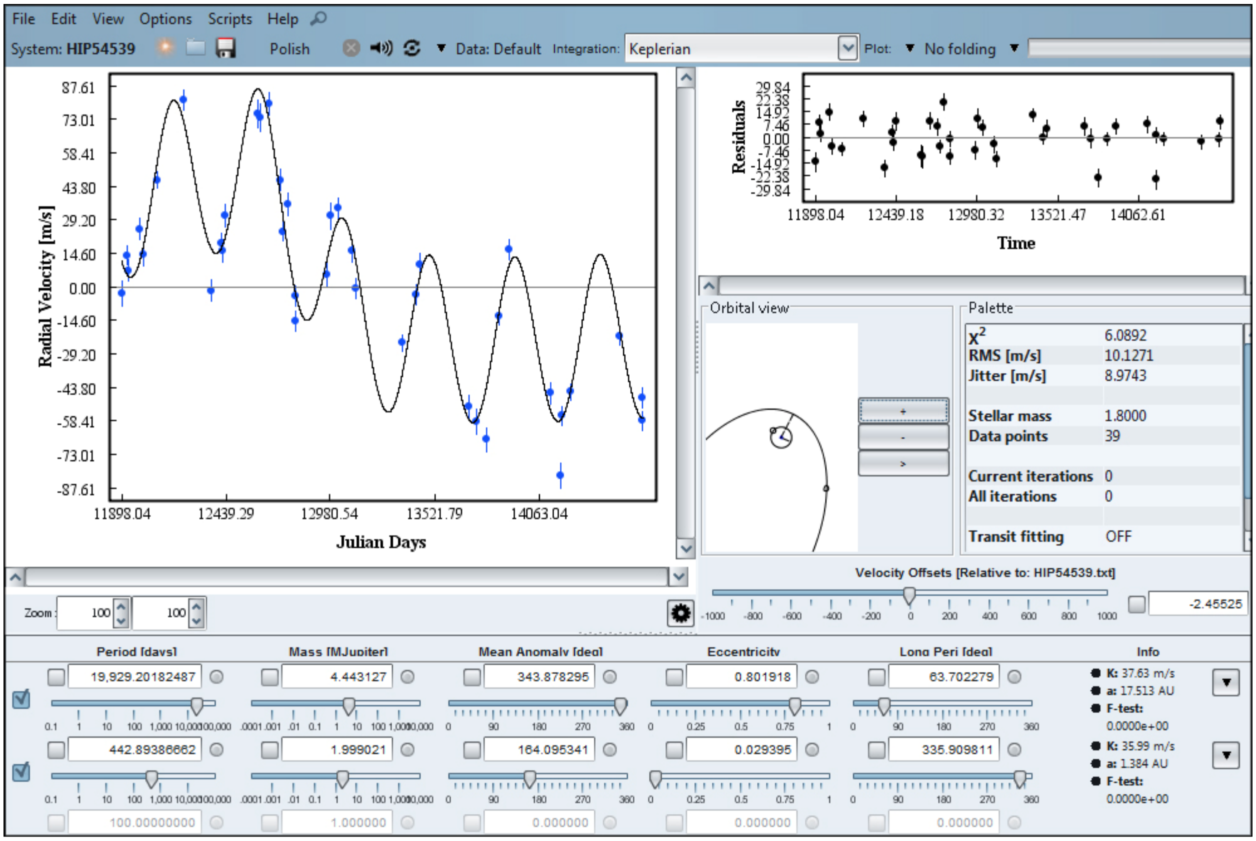

Figure 22. HIP 54539 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
6.0892	10.1271	8.9743	1.8000	39

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	19,929.20182487	4.443127	343.878295	0.801918	63.702279	-2.45525
2	442.8938666	1.999021	164.095341	0.029395	335.909811	-2.45525

HIP 96516:

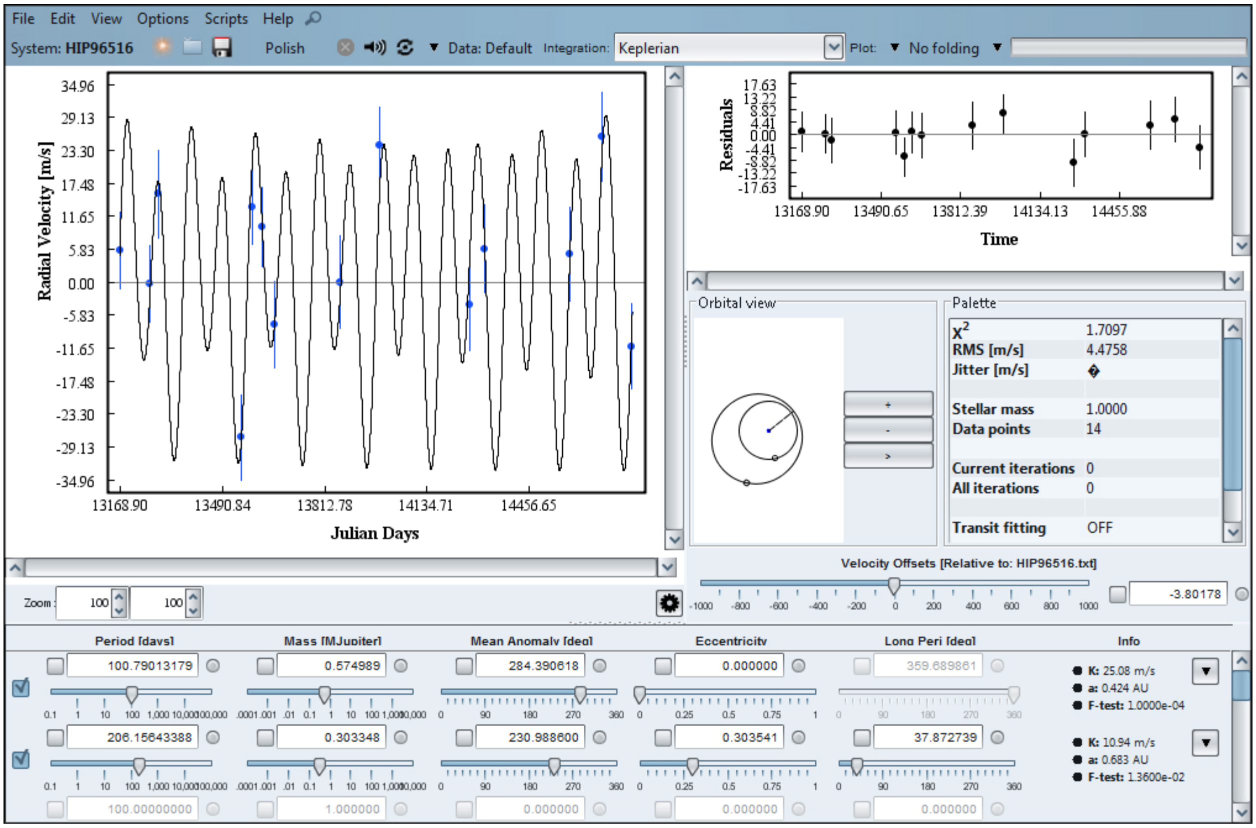

Figure 23. HIP 96516 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
1.7097	4.4758	n/a	1.0000	14

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	100.79013179	0.574989	284.390618	0.000000	n/a	-3.80178
2	206.15643388	0.303348	230.988600	0.303541	37.872739	-3.80178

Unusually Short Period:

HIP 59316:

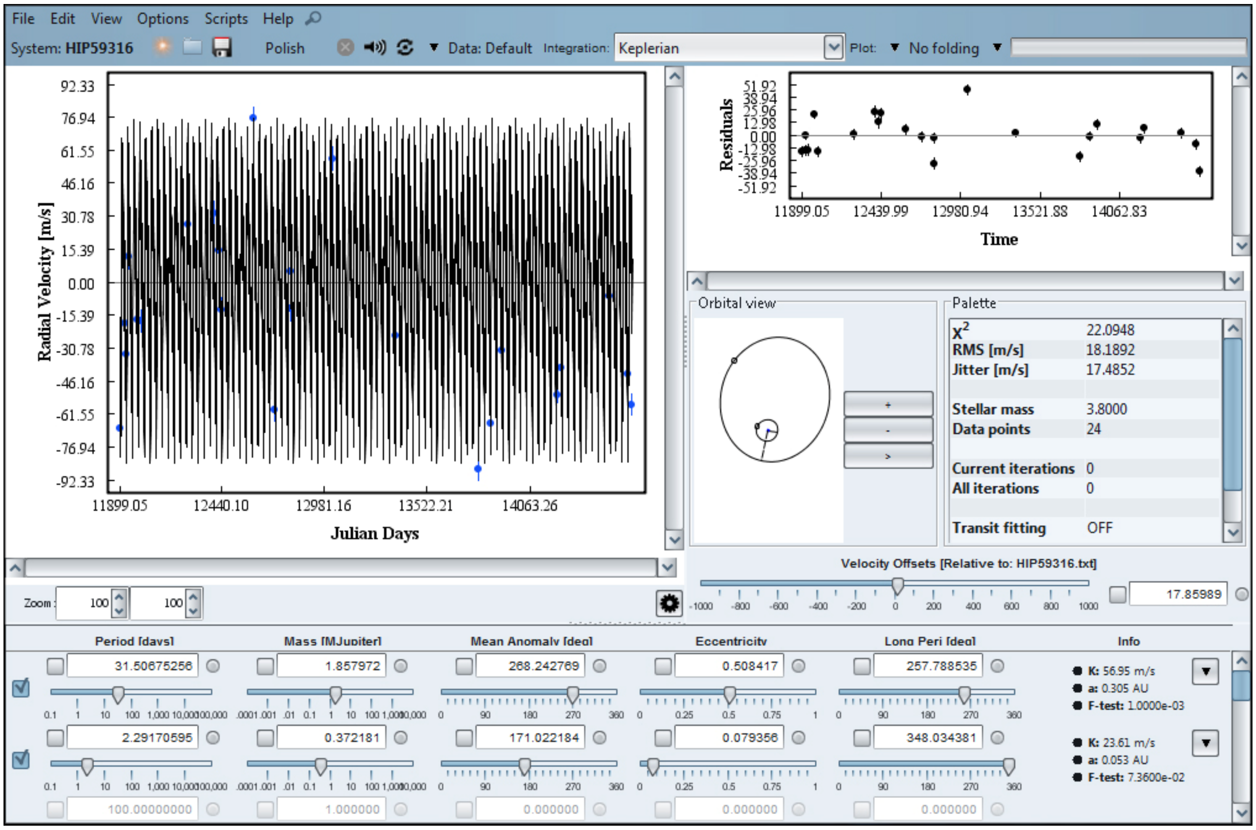

Figure 24. HIP 59316 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
22.0948	18.1892	17.4852	3.8000	24

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	31.50675256	1.857972	268.242769	0.508417	257.788535	17.85989
2	2.29170595	0.372181	171.022184	0.079356	348.034381	17.85989

HIP 111362:

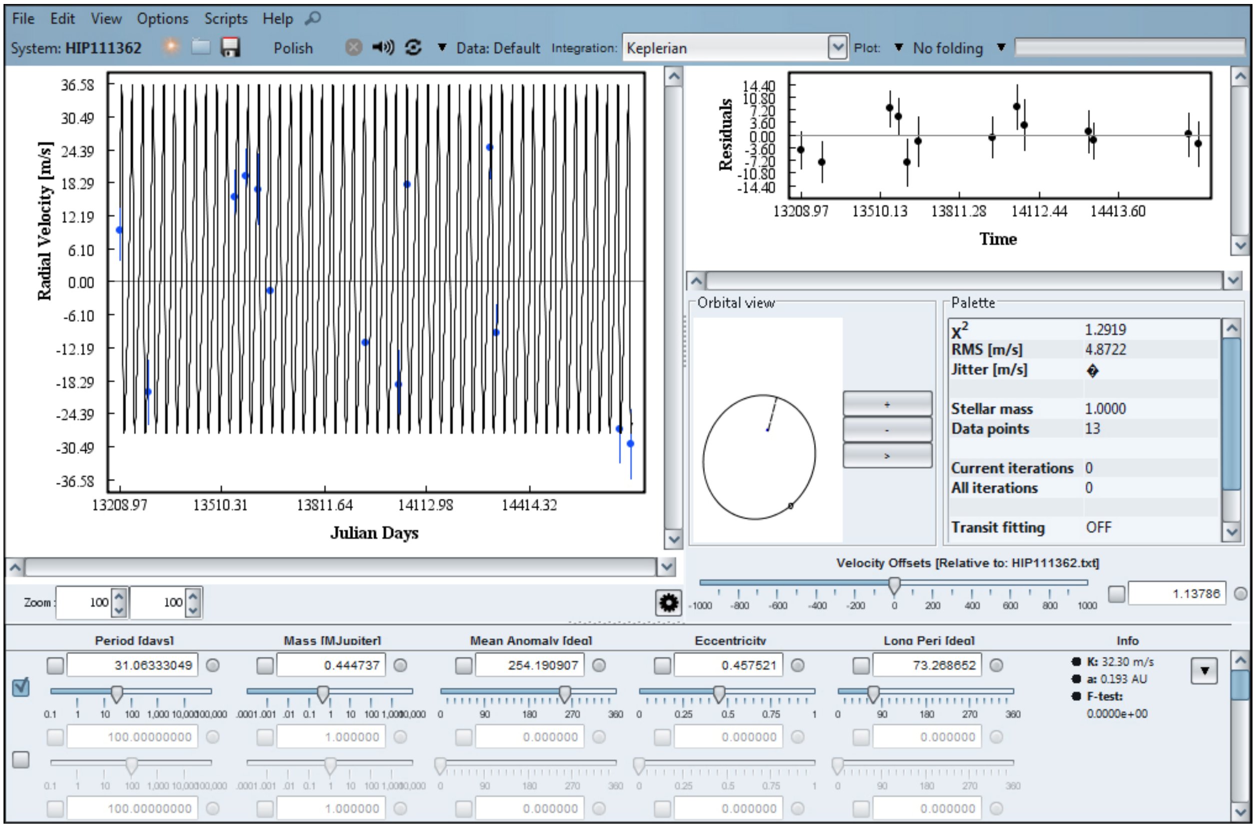

Figure 25. HIP 111362 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
1.2919	4.8722	n/a	1.0000	13

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	31.06333049	0.444737	254.190907	0.457521	73.268652	1.13786

Other Uninteresting:

HIP 67459:

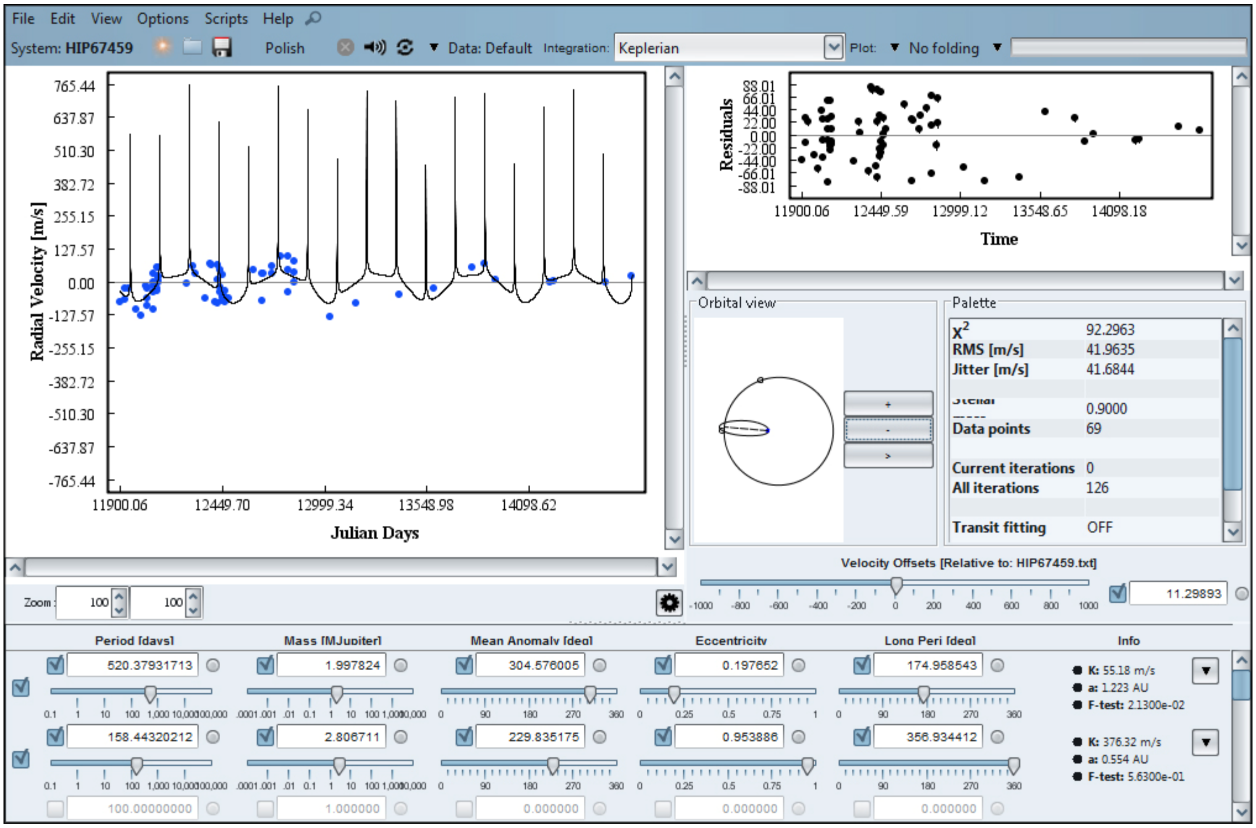

Figure 26. HIP 67459 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
92.2963	41.9635	41.6844	0.9000	69

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	520.37931713	1.997824	304.576005	0.197652	174.958543	11.29893
2	158.44320212	2.806711	229.835175	0.953886	356.934412	11.29893

HIP 113562:

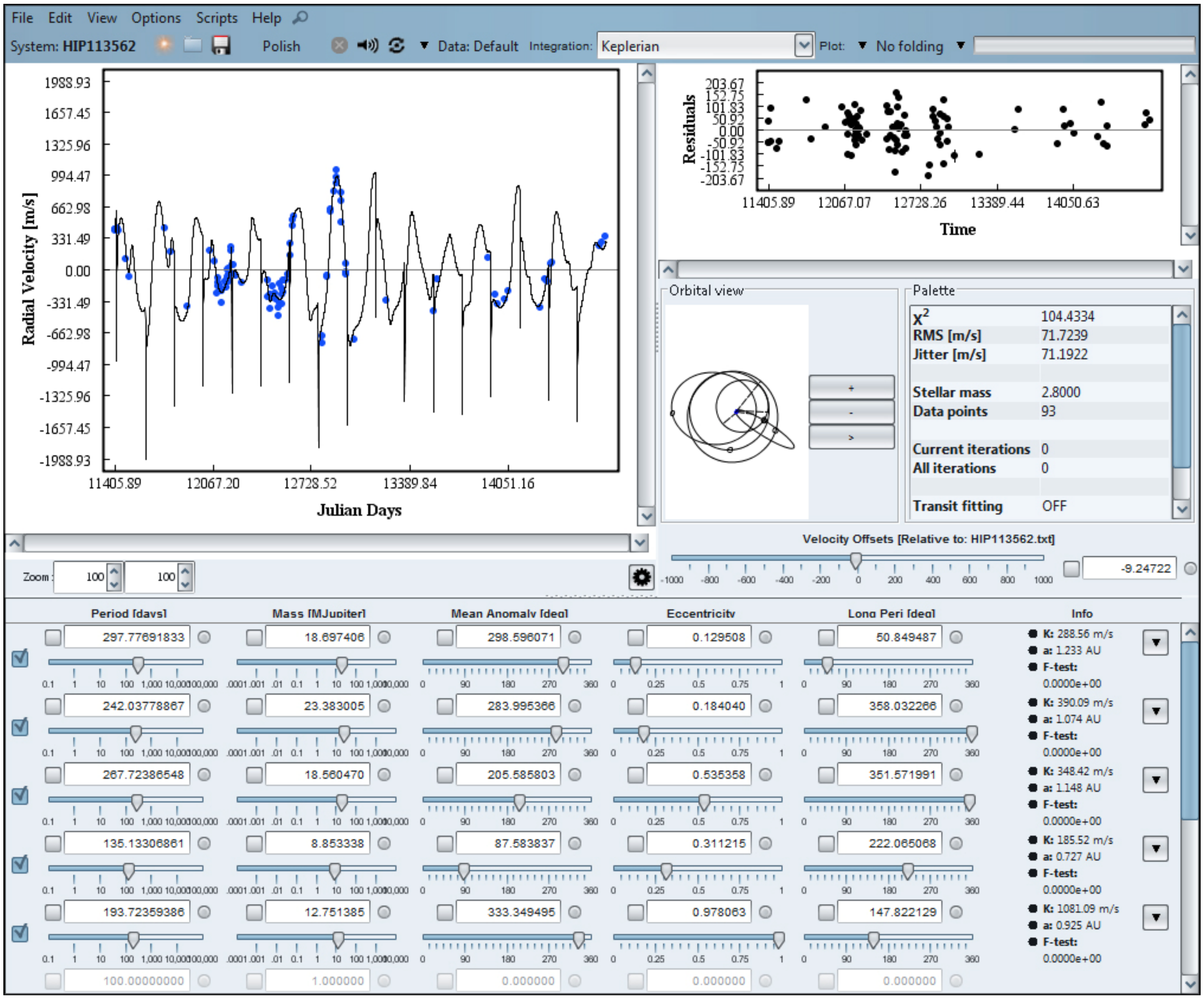

Figure 27. HIP 113562 Overview

X^2	RMS (m/s)	Jitter (m/s)	Stellar Mass (M_{SUN})	# of Data Points
104.4334	71.7239	71.1922	2.8000	93

Planet	Period (days)	Mass (M_J)	Mean Anomaly (deg)	Eccentricity	Long. Period (deg)	Vel. Offset (m/s)
1	297.77691833	18.697406	298.596071	0.129508	50.849487	-9.24722
2	242.03778867	23.383005	283.995366	0.184040	358.032266	-9.24722
3	267.72386548	18.560470	205.585803	0.535358	351.571991	-9.24722
4	135.13306861	8.853338	87.583837	0.311215	222.065068	-9.24722
5	193.72359386	12.751385	333.349495	0.978063	147.822129	-9.24722

Please refer to Appendix B for better views of the “Radial Velocity vs. Julian Date” graphs for the stars appearing above.

Discussion

Planet Candidates:

HIP 20889:

This is potentially a good planet candidate because the fit has a good correlation with the data, but there is relatively little data and a few are not on the fit. Nonetheless, all the orbital parameters look to be in good shape. The main concern is that the fit starts to fall off towards the earlier Julian dates. With much more data concentrated with later dates, the fit is clearly better in these areas.

HIP 34693:

From the look of the fit, this happens to be a good planet candidate. The first planet has a respectable period, shorter than an Earth year. The second has a period about double that of Mars's. Both masses are well below the brown dwarf limit and the eccentricities are also very low, where the second is almost perfectly circular. There are a few data points that don't lie on the fit itself but an overwhelming majority of them do. There is clearly an oscillating pattern in the data and is made readily apparent through the large number of data points.

HIP 34987:

Everything about this fit points to a being planet here. The only orbital parameter that calls attention is the low eccentricity of the orbit, but one should be cautious because there are only 7 data points for this fit. This is too few to give a definitive answer about whether there is a planet or not. Although if you notice the fit lies almost directly on all the data points and doesn't rely on the error bars to make the fit work. More data should be taken to see if there is something here.

HIP 60202:

Even though there are only 26 data points, there is an obvious oscillating pattern in the data. This oscillation is much more apparent in the later Julian days, where the data was taken in more concentrated amounts. There are a few data points not directly on the fit itself, but the overall correlation is very good. None of the orbital parameters are out of the ordinary. Data should be taken more frequently and consistently in order to get a better fit and confirm the existence of a planet.

HIP 88048:

This is perhaps the most interesting star in the first data set and the best planet candidate. The fit is almost perfect and there is nothing overly strange about the orbital parameters for either planet. There were a lot of data points, which allowed the fit to be relatively precise. Both planets have slight eccentricities but nothing too out of the ordinary. The orbits don't overlap and aren't even that close together, so long term stability would seem reasonable. The planet masses aren't too little or too large and X^2 is also very low.

HIP 114855:

There is very good evidence for the existence of a planet about this star. The large amount of data, taken over a short period helps to confirm this. If you were to look at the data without a fit, you would immediately be able to tell there is an oscillating pattern. A good majority of the data points lie directly on the fit, with only a few scattered points. Most of the orbital parameters look good. Only the eccentricity seems to raise questions because the orbit is almost a perfect circle. It is possible to have an orbit with an eccentricity this low, but it is rarely observed.

Binary Stars:

HIP 76425:

It should be quite obvious that there is something different about this fit. None of the orbital parameters are out of the ordinary, except for the mass. The extremely large mass tells you that this cannot be a planet. In fact, HIP 76425 must be a binary star. 276 M_J is about ¼ M_{SUN}. The KPD project tried to eliminate the known binaries because they are not useful grid stars for SIM. This fit shows that sometimes binary stars do happen to sneak by. If you notice the velocity offset is stuck at the minimum value of -1000 m/s. This is probably one of the major causes for the poor X^2 value because the velocity offset is probably more than -1000 m/s.

HIP 95785:

This star exhibits some of the same properties as HIP 76425. The mass is well above the brown dwarf limit, which tells us this is probably a binary star. The long period is also typical of binaries. The eccentricity is unusually low and unlike HIP 76425 the velocity offset is not maxed.

Few Data Points:

HIP 27629:

This is an interesting fit, although it may not be fully believable. There are such few data points that it's hard to know if there really is two planets. Some peculiar orbital parameters for both starts include their period, masses, and eccentricity. The period of the second planet seems a little short, especially since it is orbiting a giant star. The masses of both planets are fairly low and it becomes increasingly difficult/unlikely to detect planets the less massive they are. Both orbits seem to be almost perfectly circular. Comparing this to what we've seen for the other potential planets, this is odd. So far a vast majority of detected extrasolar planets don't have perfectly circular orbits. Even within our own solar system, planets do not have perfectly circular orbits. The second planet is somewhat questionable, unlike the first, because of its very short period and unusually low mass. It would be wise to take more data on this star and see what is happening.

The evidence for a second planet may actually be a result of stellar pulsations rather than an orbiting body. Stars can naturally vary in size on relatively short timescales. Our own sun vibrates in and out by a tiny amount (Freedman & Kaufmann III 2007). Unlike the sun though, some stars vary or pulsate on a larger scale. This pulsation could trick the Console into thinking there is a planet when there isn't because the star pulsing inwards and outwards causes a Doppler shift in its stellar spectrum. If this pulsation were to happen with a period of about a few months, the analysis might think it's a planet.

HIP 78990:

The fit for two planets seems to correlate well to the data points and does not rely too heavily on the error bars to work. However, 11 data points is not many compared to the 100+ seen for some of the planet candidates. The data is taken at such wide intervals that it's hard to say if this fit is entirely accurate. The mass of the second planet does seem a little low, but not unreasonable. All other orbital parameters are okay.

Impossible Orbits:

HIP 38253:

The fit has a X^2 of 52.7416, which could be better but it's not too bad for a 5 planet fit. Looking at the orbital view window, it becomes readily apparent that even though the fit somewhat correlates to the data, the orbits could never exist. The orbits of the first two planets (two largest orbits) come into contact on the right side. The orbits of the other three also come into very close contact. The orbit of the fifth planet intersects that of the first planet and comes into contact with the orbit of the second. These orbits would not be stable in the short or long term. There is too much intersection and contact for the orbits to be realistic.

HIP 79195:

The fit for this star correlates very well to the data. The X^2 is very low at 1.3580. Looking at the orbital view, it should be obvious that these orbits could not work. The orbit of the first planet intersects the orbits of the other two (second and third). The second and third orbits do come near each other, but not enough to definitely say that they would interfere with each other in the long term. The only thing that makes this fit unusable, aside from the first planet having a mass just above the brown dwarf limit, is that the first orbit is intersecting the others.

Other Interesting:

HIP 54539:

There seems to be a pattern in the data according to the fit but there are several data points that are pretty far off. The masses of the planets seem to be good, they not too small. The fit is definitely interesting but there are a few characteristics that should catch your attention. The period of the first planet, a little over 54 years, is extremely long compared to the second. There is nothing physically wrong with this but it is a bit strange. We have only been taking data for this star for a few years, so it is a little difficult to map out a planet with a ≈54 year period. The eccentricity of the first planet is also very large. It is possible to stay in orbit with such a large eccentricity but there may be some stability problems in the long run because of the second planet.

HIP 96516:

There are a few orbital parameters that prevent this star from being a good planet candidate. The masses of both planets are fairly low, especially for the second planet. The orbit of the first planet is a perfect circle, which as mentioned before is quite rare. The data points have large error bars but this isn't so much of a concern because the fit lies directly on most of the data points and doesn't rely on the error bars to work. The major reason why this star wasn't considered a planet candidate was because the two orbits come in close to each other, as seen in the orbital view window. This would make the stability of orbits questionable and thus not a planet candidate because the orbits need to be stable for planets to exist.

Short Periods:

HIP 59316:

The correlation to the data is decent. The X^2 isn't too large but it could be lower. Aside from the low mass of the second planet, the major problem with this fit is that that the orbital periods are too short. Even though the period of the first planet is over 13 times longer than the second planet, both periods are so short that they would have to be orbiting within the star.

HIP 111362:

This fit has nearly a perfect correlation to the data and the orbital parameters look good, aside from the low mass. Like the first planet in HIP 59316, a period of about a month is too short to orbit a giant star.

Other Uninteresting:

HIP 67459:

There is a lot of data, but the points seem to be scattered about randomly. There isn't an obvious pattern in that the Console could easily fit to. In order to make a fit, the Console resorts to making the second planet have a very high eccentricity. Even with this extreme orbital parameter, the fit is still not that good. The big X^2 of 92.2963 shows that the fit doesn't correlate well.

HIP 113562:

There does seem to have some oscillatory pattern but the fit is still not good. The program resorts to giving large eccentricities to the planets in order to improve the fit. In general, as more planets are added the fit improves, but even with 5 planets the fit is still bad with a X^2 of 104.4334. The Console also assigns very large masses to the planets, which seems unlikely because the host star only has a mass of 2.8 M_{SUN}.

Conclusion

As is often the case, major individual projects tend to lead to smaller ones. The KPD project began by looking at only 86 K-giants and has since grown four fold. About a fifth of the stars being observed don't seem to have anything interesting happening. For those that did, it was decided that many could not support planets according to their orbital parameters. These stars gave impossible orbits, were classified as binaries, or needed more data and thus they were ruled out as planet candidates. The number of stars that appeared to support planetary systems comprised only a very small portion of the total observed stars.

Using the Systemic Console I have presented evidence that there are likely planetary systems that have yet to be discovered or published around six of the 373 observed K-giant stars. These stars shown the most convincing case for extrasolar planets, particularly because they had the most data points, to support their fits compared to the other candidates. Looking at the fits, there are very obvious oscillating patterns, corresponding to the stellar wobble in the stars. This is likely caused by the presence of large planets.

There are potentially planetary systems around a few stars with relatively little radial velocity data, however due to the lack of data the fits weren't of good precision to definitively claim there are planets around them. More data needs to be taken, in a higher concentration, to improve the fits or show there is no planet(s) orbiting. The big problem with having such few data points is that it is very easy to tweak the orbital parameters in order to make almost any fit work. It takes some effort to ensure that the proposed fit is indeed the correct one.

There were also several other stars that seemed like they would be good planet candidates but one or two parameters were off, such as in the case of HIP 54539 and HIP 96516. If more data were to be taken over a long time period, it may be possible that the fits improve to a point that these stars do upgrade to planet candidate status. Until then, they will remain the Other Interesting category.

HIP 76425 was a special case to show two points. First, there are limits to what the Systemic Console can do. The velocity offset was pinned at the minimum limit. If for some reason a planetary system would cause the host star to have a radial velocity of more than 1000 m/s, it cannot be accurately accounted for by the program. Second, HIP 76425 is known to be a spectroscopic binary[4]. Since the analysis was able to determine that it was a binary star, this shows that the Console does work, if used properly. If it was able to detect the binary nature of HIP 76425 from its radial velocity data, then it should be able to detect potential planets around stars, using the same type of data. So in effect, this binary star was used to show that the analysis for the other stars is useful.

[4] Based on SIMBAD data about HIP 76425 located at http://simbad.u-strasbg.fr/simbad/

Although the Console seems to work in a majority of cases, it's still not perfect. It can often find ways to make a fit for the data even though the planetary orbits could not possibly exist. It is important that the user of the Console pays strict attention to the orbital parameters and to often check the orbital view window so as to insure that stars aren't mistaken as planet candidates when the orbits don't work.

There are features of the Console which were not utilized or mentioned in this paper. A useful feature tests the orbital evolution and stability of the fits. For a more thorough analysis of the data, this feature should be utilized to further confirm the evidence of potential extrasolar planets. As the field for extrasolar planet detection continues to grow, the KPD project should consider adding even more K-giants to their observation list. It's certainly possible for them to also monitor other types of stars and discover what interesting characteristics they might have. It will also be exciting to see if SIM can make good on its claim to detect Earth like planets because that will bring us one step closer to finding other intelligent life in the universe.

References

Marcy, G.W. & Butler, R.P. 2000, PASP, 112, 137

Butler, R.P., Marcy, G.W., Williams, E., et al. 1996, PASP, 108, 500

Frink, S., Quirrenbach, A., Fischer, D., Röser, S., & Schilbach, E. 2001, PASP, 113, 173

Mitchell, David S. (2004). A High Precision Radial Velocity Survey of K Giants (Doctoral dissertation, University of California San Diego, 2004)

Freedman, Roger A., & Kaufmann III, William J. (2007). Universe: Eighth Edition. New York, NY: W.H. Freeman and Company

Taylor, John, Zafiratos, Chris, & Dubson, Michael A. (2003). Modern Physics for Scientists and Engineers: Second Edition. San Francisco, CA: Benjamin Cummings

Appendix A

Planet Candidates

1st Data Set

1. HIP 34693
2. HIP 88048
3. HIP 114855

2nd Data Set

1 HIP 20889
2. HIP 60202
3. HIP 34987

Binary Stars

1st Data Set

1. HIP 8198
2. HIP 14668
3. HIP 15861
4. HIP 36388
5. HIP 36616
6. HIP 43409
7. HIP 46750
8. HIP 50366
9. HIP 53229
10. HIP 72210
11. HIP 73133
12. HIP 80343
13. HIP 87808
14. HIP 92747
15. HIP 93429
16. HIP 100587
17. HIP 102488
18. HIP 102978
19. HIP 113084

2nd Data Set

1. HIP 3607
2. HIP 4510
3. HIP 5742
4. HIP 12093
5. HIP 13965
6. HIP 18212
7. HIP 19009
8. HIP 20241
9. HIP 20268
10. HIP 20885
11. HIP 22220
12. HIP 24822
13. HIP 27588
14. HIP 33449
15. HIP 35476
16. HIP 37740
17. HIP 38962
18. HIP 40305
19. HIP 46652
20. HIP 48356
21. HIP 48802
22. HIP 58654
23. HIP 58948
24. HIP 76425
25. HIP 89918
26. HIP 94302
27. HIP 95785
28. HIP 103360
29. HIP 110532
30. HIP 118209

Impossible Orbit(s)

1st Data Set

1. HIP 33856
2. HIP 34387
3. HIP 38253
4. HIP 39079
5. HIP 39177
6. HIP 40526
7. HIP 47431
8. HIP 52943
9. HIP 55282
10. HIP 69427
11. HIP 73620
12. HIP 74732
13. HIP 79195
14. HIP 84671
15. HIP 85355
16. HIP 85693
17. HIP 91117
18. HIP 104060
19. HIP 109023
20. HIP 109492
21. HIP 113562
22. HIP 115669

2nd Data Set

1.	HIP 10642	6.	HIP 31688	11.	HIP 77738	16.	HIP 99951
2.	HIP 15696	7.	HIP 64962	12.	HIP 85715	17.	HIP 103294
3.	HIP 20732	8.	HIP 67210	13.	HIP 91105	18.	HIP 107188
4.	HIP 28812	9.	HIP 71832	14.	HIP 94820	19.	HIP 110602
5.	HIP 29575	10.	HIP 74666	15.	HIP 97118		

Few Data Points

1st Data Set

1.	HIP 53316
2.	HIP 72571
3.	HIP 78442
4.	HIP 93864

2nd Data Set

1.	HIP 2942	18.	HIP 27483	35.	HIP 44936	52.	HIP 76810
2.	HIP 3231	19.	HIP 27629	36.	HIP 46457	53.	HIP 78990
3.	HIP 3760	20.	HIP 28814	37.	HIP 46952	54.	HIP 79882
4.	HIP 4587	21.	HIP 29379	38.	HIP 47029	55.	HIP 80331
5.	HIP 6999	22.	HIP 31159	39.	HIP 47570	56.	HIP 80894
6.	HIP 11220	23.	HIP 32249	40.	HIP 63533	57.	HIP 95352
7.	HIP 14915	24.	HIP 32562	41.	HIP 63608	58.	HIP 100064
8.	HIP 16358	25.	HIP 33421	42.	HIP 65301	59.	HIP 101870
9.	HIP 17103	26.	HIP 34267	43.	HIP 66098	60.	HIP 104459
10.	HIP 19483	27.	HIP 36041	44.	HIP 66907	61.	HIP 106481
11.	HIP 19996	28.	HIP 37364	45.	HIP 67545	62.	HIP 110003
12.	HIP 20250	29.	HIP 40866	46.	HIP 67787	63.	HIP 110023
13.	HIP 20252	30.	HIP 41704	47.	HIP 70469	64.	HIP 112242
14.	HIP 20455	31.	HIP 43531	48.	HIP 72934	65.	HIP 112748
15.	HIP 21743	32.	HIP 43813	49.	HIP 73166	66.	HIP 115152
16.	HIP 24294	33.	HIP 43834	50.	HIP 73555		
17.	HIP 25247	34.	HIP 44154	51.	HIP 75352		

Other Interesting

1[st] Data Set

1. HIP 5364
2. HIP 6537
3. HIP 9110
4. HIP 9347
5. HIP 16335
6. HIP 19011
7. HIP 21421
8. HIP 23015
9. HIP 23123
10. HIP 30457
11. HIP 30720
12. HIP 31592
13. HIP 31700
14. HIP 33160
15. HIP 34033
16. HIP 36848
17. HIP 36962
18. HIP 43923
19. HIP 46390
20. HIP 46982
21. HIP 47959
22. HIP 51069
23. HIP 53261
24. HIP 53740
25. HIP 53781
26. HIP 54539
27. HIP 57399
28. HIP 60742
29. HIP 65323
30. HIP 69673
31. HIP 71053
32. HIP 75730
33. HIP 79540
34. HIP 80693
35. HIP 84380
36. HIP 85139
37. HIP 87933
38. HIP 90067
39. HIP 91004
40. HIP 98337
41. HIP 101986
42. HIP 102422
43. HIP 107315
44. HIP 109602
45. HIP 109754
46. HIP 110986
47. HIP 114449
48. HIP 115438

2[nd] Data Set

1. HIP 4422
2. HIP 10729
3. HIP 13288
4. HIP 16989
5. HIP 27280
6. HIP 44406
7. HIP 44659
8. HIP 66320
9. HIP 67057
10. HIP 68581
11. HIP 73909
12. HIP 89008
13. HIP 96516
14. HIP 107382
15. HIP 109972

Short Period(s)

1[st] Data Set

1. HIP 4906
2. HIP 13701
3. HIP 14838
4. HIP 21248
5. HIP 22860
6. HIP 32814
7. HIP 33914
8. HIP 35907
9. HIP 37447
10. HIP 38375
11. HIP 41075
12. HIP 41909
13. HIP 42402
14. HIP 42911
15. HIP 47189
16. HIP 48445
17. HIP 55716
18. HIP 59316
19. HIP 59847
20. HIP 61571
21. HIP 64078
22. HIP 68895
23. HIP 74239
24. HIP 75944
25. HIP 77853
26. HIP 78132
27. HIP 81660
28. HIP 85888
29. HIP 88636
30. HIP 88839
31. HIP 89962
32. HIP 90139
33. HIP 90496
34. HIP 94779
35. HIP 113686
36. HIP 115830

2[nd] Data Set

1. HIP 1354
2. HIP 3031
3. HIP 4914
4. HIP 7906
5. HIP 10234
6. HIP 35615
7. HIP 37204
8. HIP 39191
9. HIP 40107
10. HIP 46880
11. HIP 48734
12. HIP 51775
13. HIP 55650
14. HIP 55797
15. HIP 56647
16. HIP 60485
17. HIP 61420
18. HIP 62103
19. HIP 64540
20. HIP 70791
21. HIP 88765
22. HIP 96327
23. HIP 97402
24. HIP 111362
25. HIP 117503

Other Uninteresting

1st Data Set

1.	HIP 379	11.	HIP 13905	21.	HIP 83000	31.	HIP 106039
2.	HIP 1562	12.	HIP 19388	22.	HIP 83254	32.	HIP 108691
3.	HIP 2497	13.	HIP 23685	23.	HIP 84950	33.	HIP 109068
4.	HIP 3179	14.	HIP 33152	24.	HIP 86742	34.	HIP 109937
5.	HIP 3419	15.	HIP 44356	25.	HIP 88684	35.	HIP 111944
6.	HIP 6732	16.	HIP 50027	26.	HIP 89826	36.	HIP 112724
7.	HIP 7607	17.	HIP 55086	27.	HIP 93085	37.	HIP 113622
8.	HIP 7884	18.	HIP 58181	28.	HIP 96229	38.	HIP 113341
9.	HIP 9884	19.	HIP 64823	29.	HIP 96459	39.	HIP 117567
10.	HIP 11432	20.	HIP 67459	30.	HIP 105497	40.	HIP 117756

2nd Data Set

1.	HIP 476	11.	HIP 42008	21.	HIP 81724	31.	HIP 104963
2.	HIP 2006	12.	HIP 44818	22.	HIP 81833	32.	HIP 105412
3.	HIP 3193	13.	HIP 45412	23.	HIP 87847	33.	HIP 105515
4.	HIP 4463	14.	HIP 52689	24.	HIP 89587	34.	HIP 110000
5.	HIP 5571	15.	HIP 55945	25.	HIP 93026	35.	HIP 111394
6.	HIP 9631	16.	HIP 59501	26.	HIP 94624	36.	HIP 111925
7.	HIP 10326	17.	HIP 60646	27.	HIP 98571	37.	HIP 112440
8.	HIP 13339	18.	HIP 71837	28.	HIP 98823	38.	HIP 112529
9.	HIP 14817	19.	HIP 72125	29.	HIP 100754	39.	HIP 114971
10.	HIP 16780	20.	HIP 77512	30.	HIP 102453	40.	HIP 117375

Appendix B

Planet Candidates:

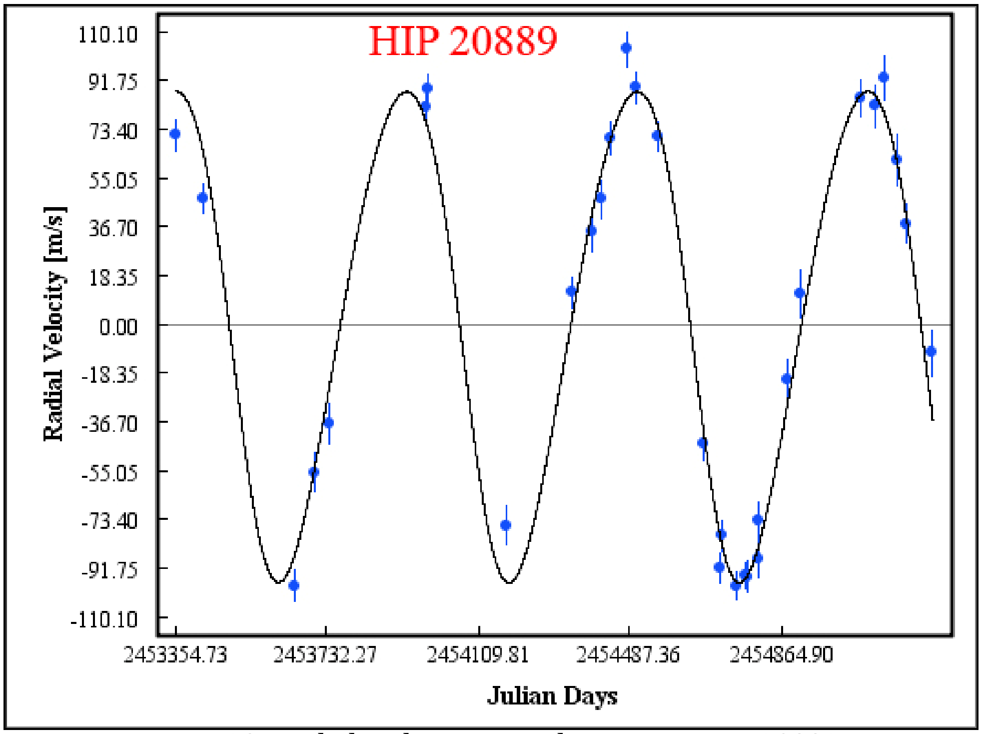

Figure 28. Radial Velocity vs. Julian Date - HIP 20889

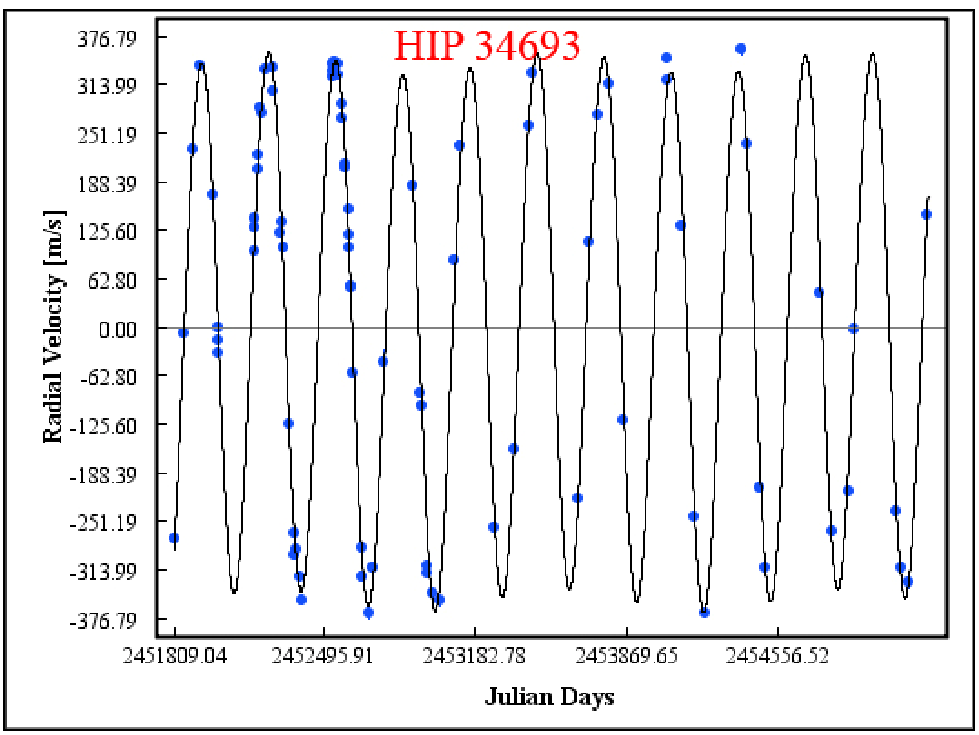

Figure 29. Radial Velocity vs. Julian Date - HIP 34693

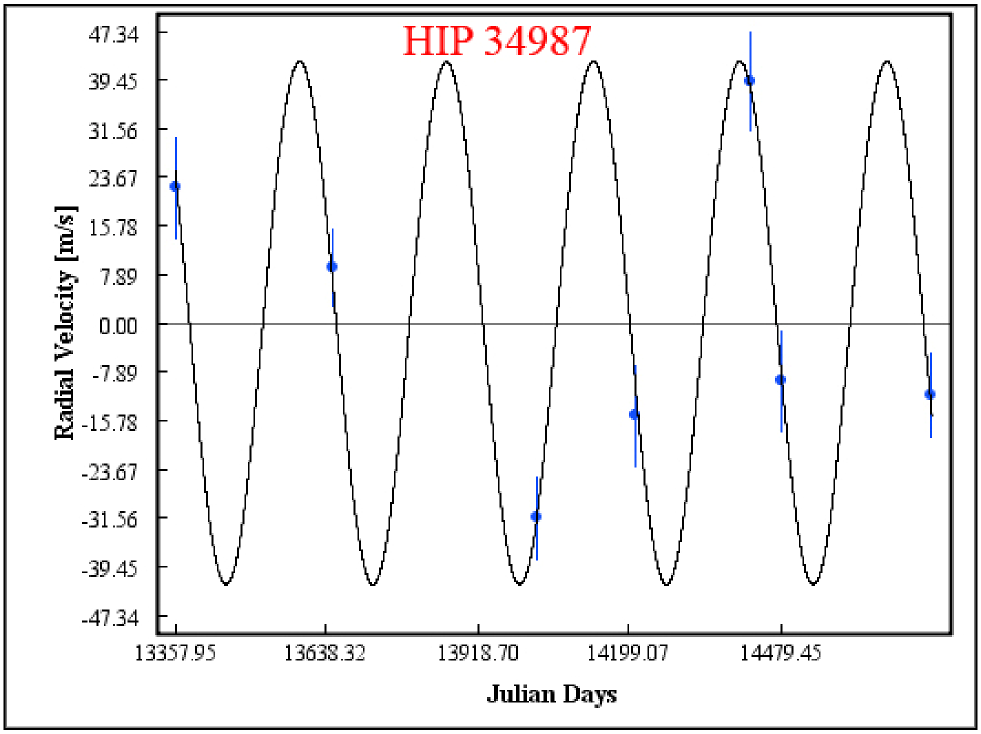

Figure 30. Radial Velocity vs. Julian Date - HIP 34987

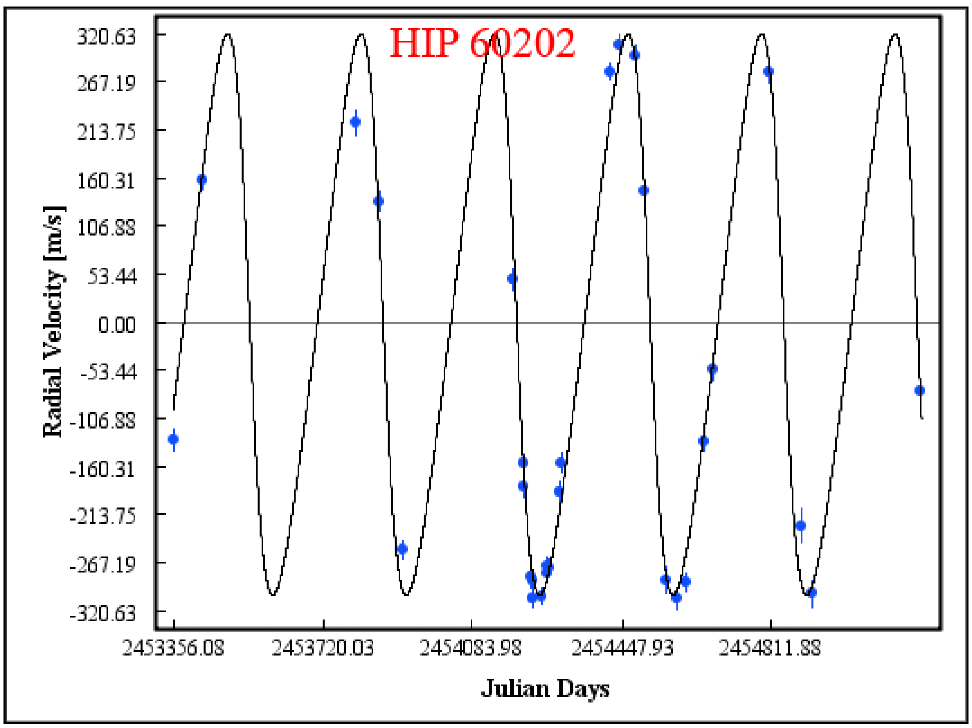

Figure 31. Radial Velocity vs. Julian Date - HIP 60202

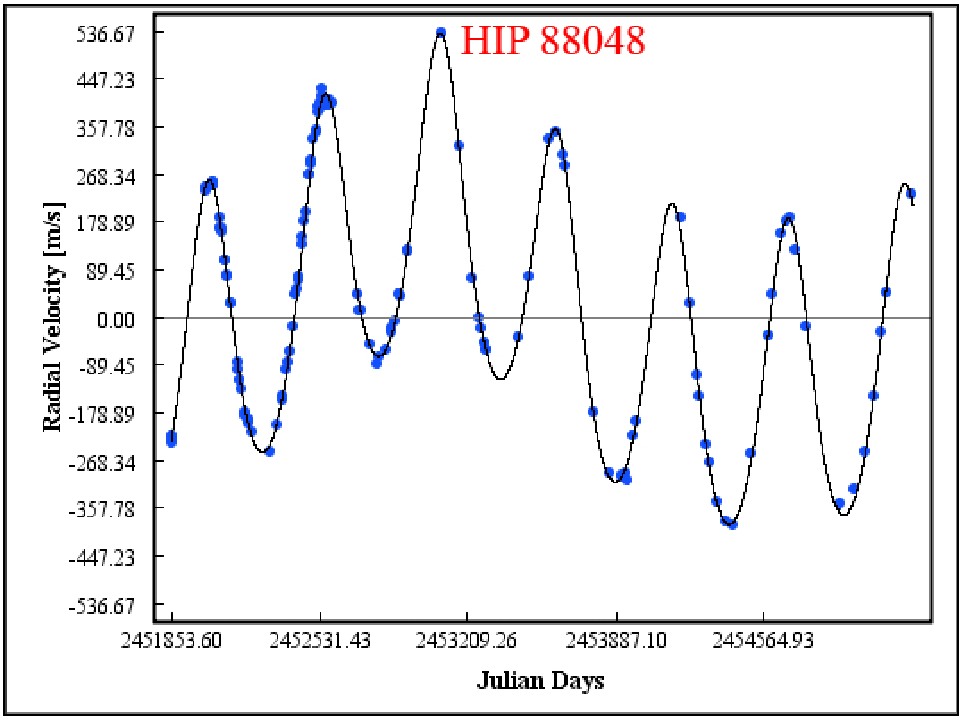

Figure 32. Radial Velocity vs. Julian Date - HIP 88048

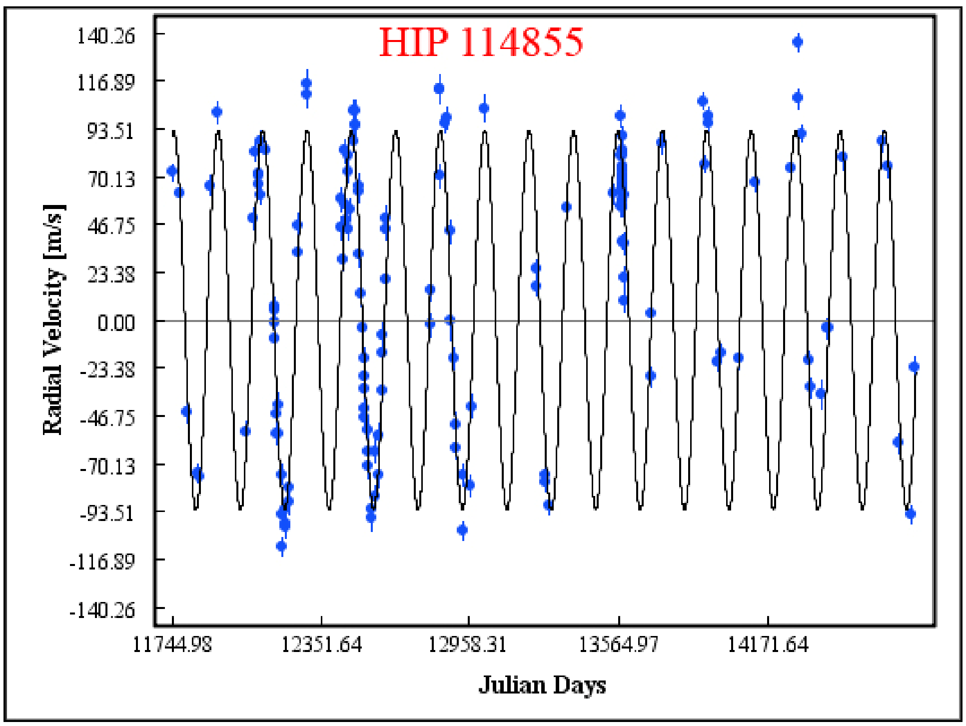

Figure 33. Radial Velocity vs. Julian Date - HIP 114855

Binary Stars:

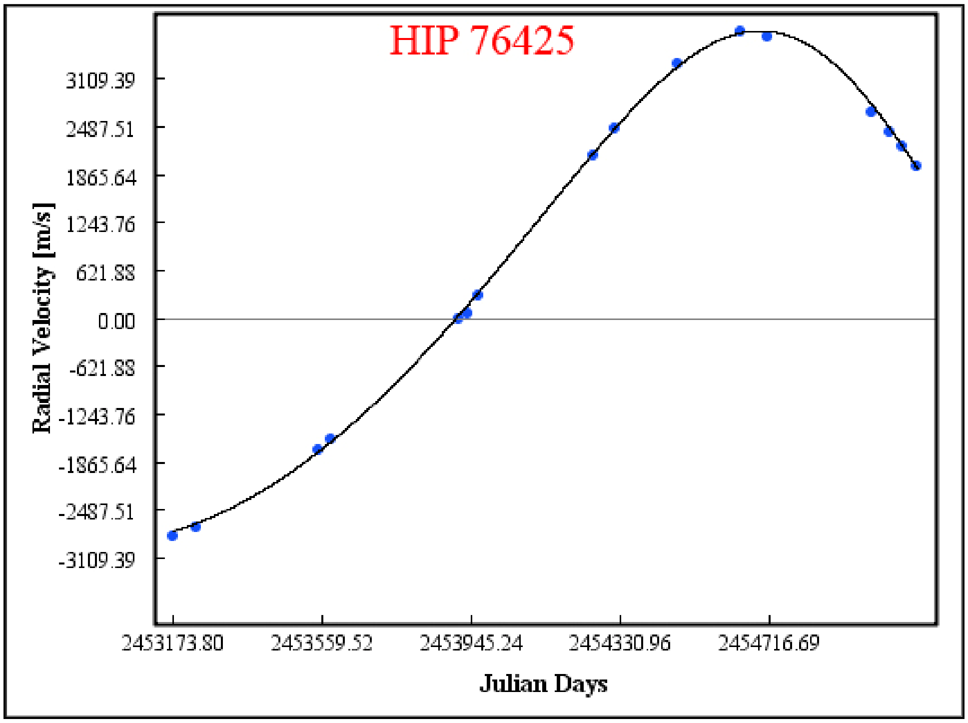

Figure 34. Radial Velocity vs. Julian Date - HIP 76425

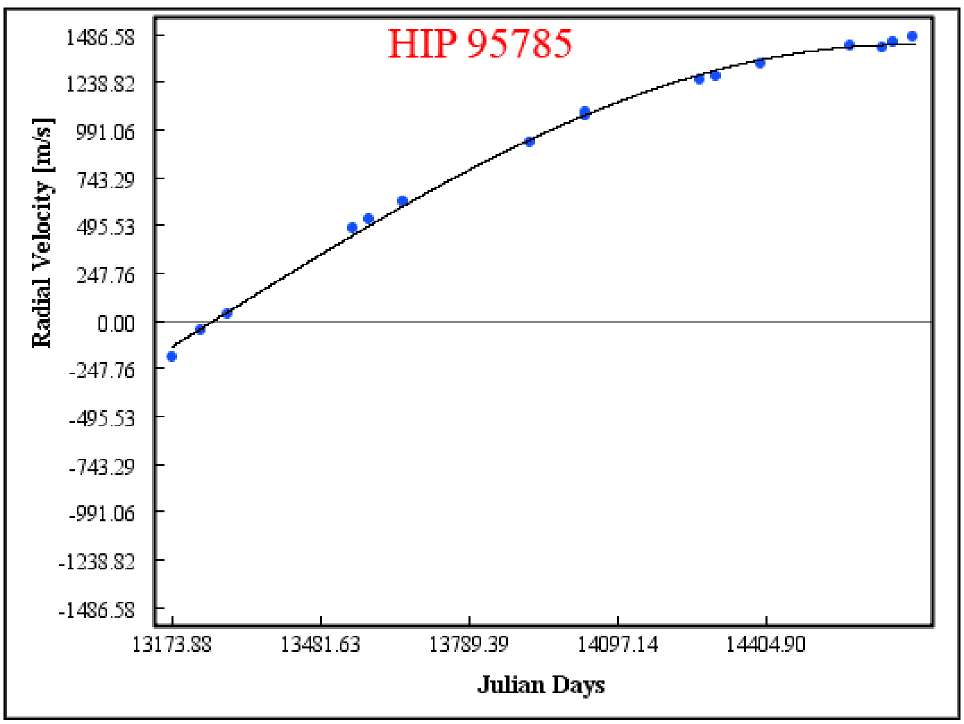

Figure 35. Radial Velocity vs. Julian Date - HIP 95785

Few Data Points:

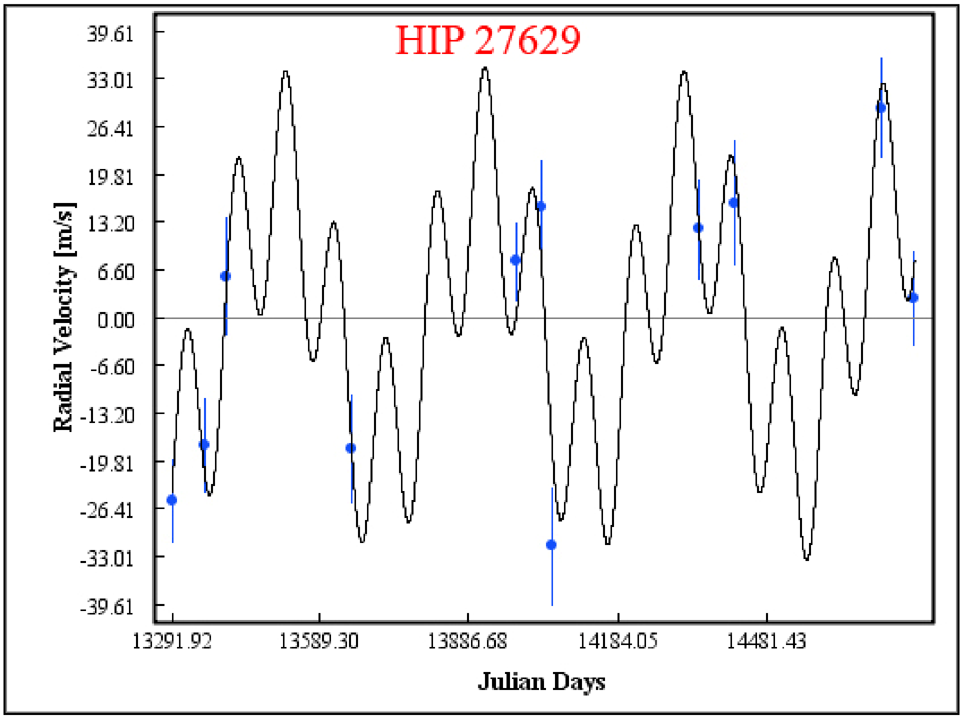

Figure 36. Radial Velocity vs. Julian Date - HIP 27629

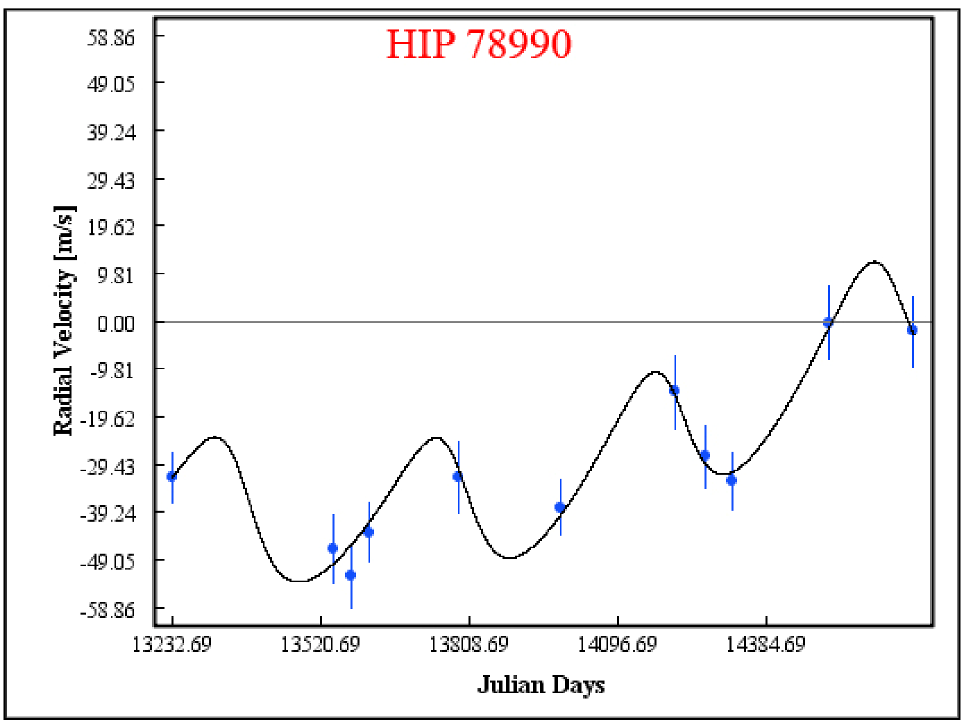

Figure 37. Radial Velocity vs. Julian Date - HIP 78990

Impossible Orbits:

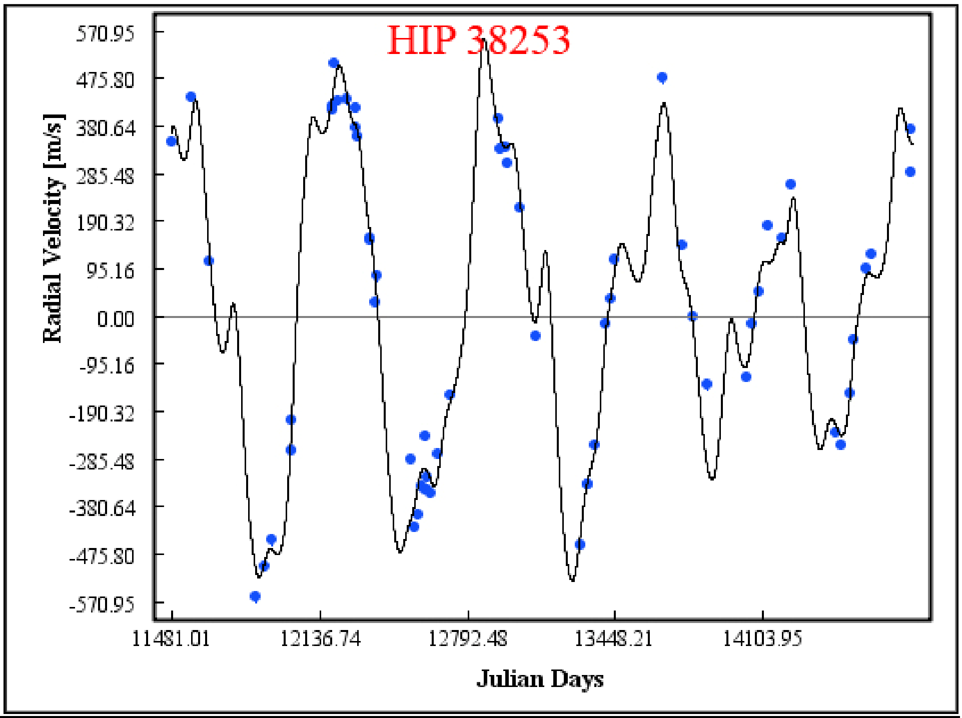

Figure 38. Radial Velocity vs. Julian Date - HIP 38253

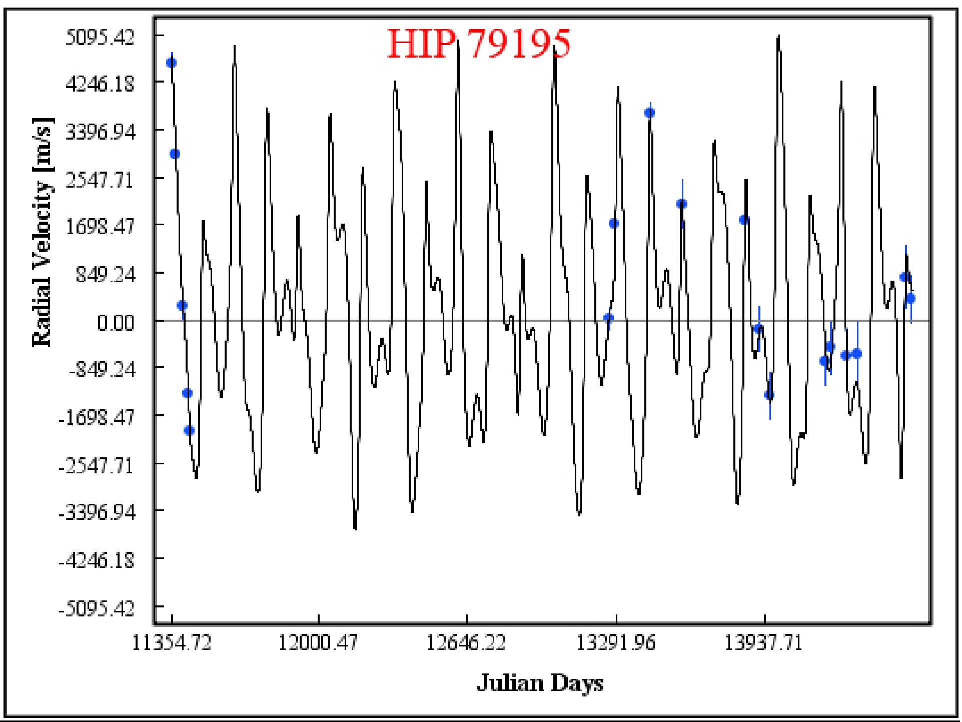

Figure 39. Radial Velocity vs. Julian Date - HIP 79195

Other Interesting:

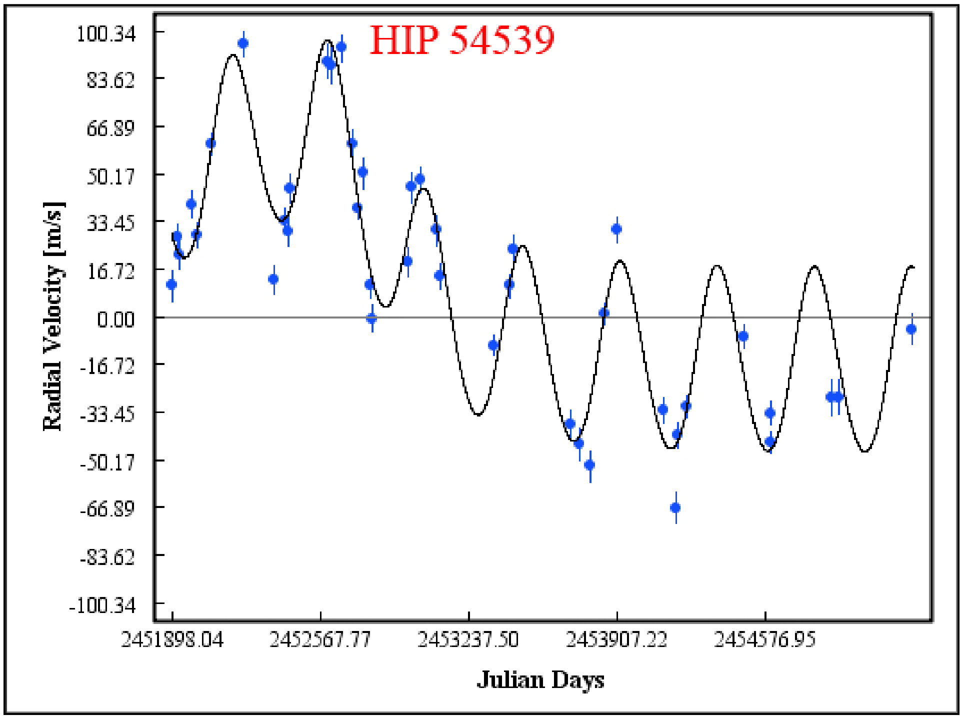

Figure 40. Radial Velocity vs. Julian Date - HIP 54539

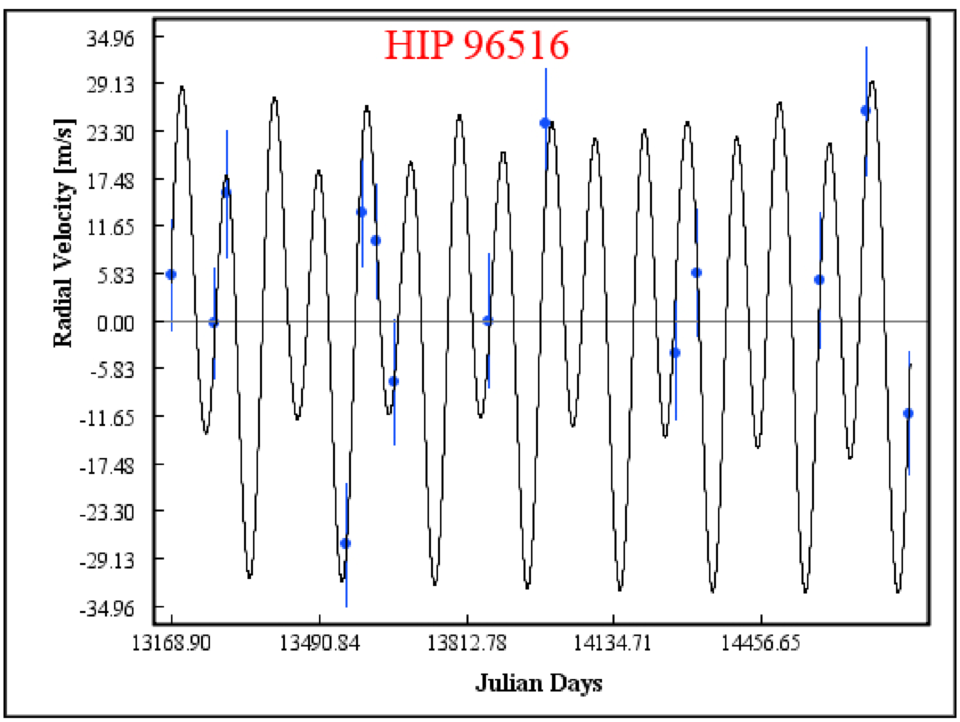

Figure 41. Radial Velocity vs. Julian Date - HIP 96516

Unusually Short Period

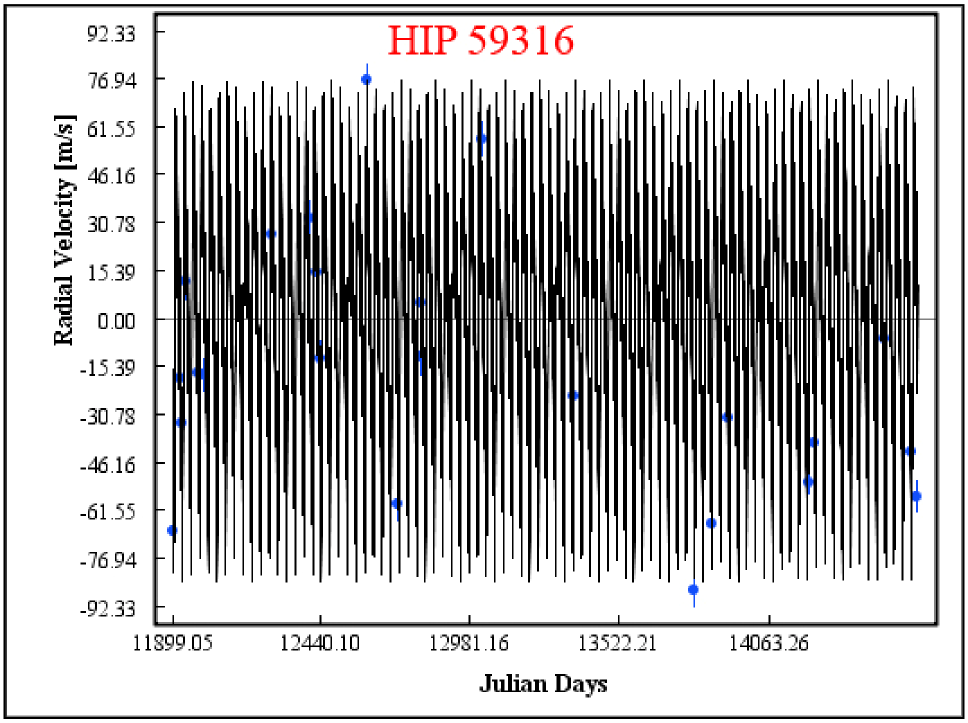

Figure 42. Radial Velocity vs. Julian Date - HIP 59316

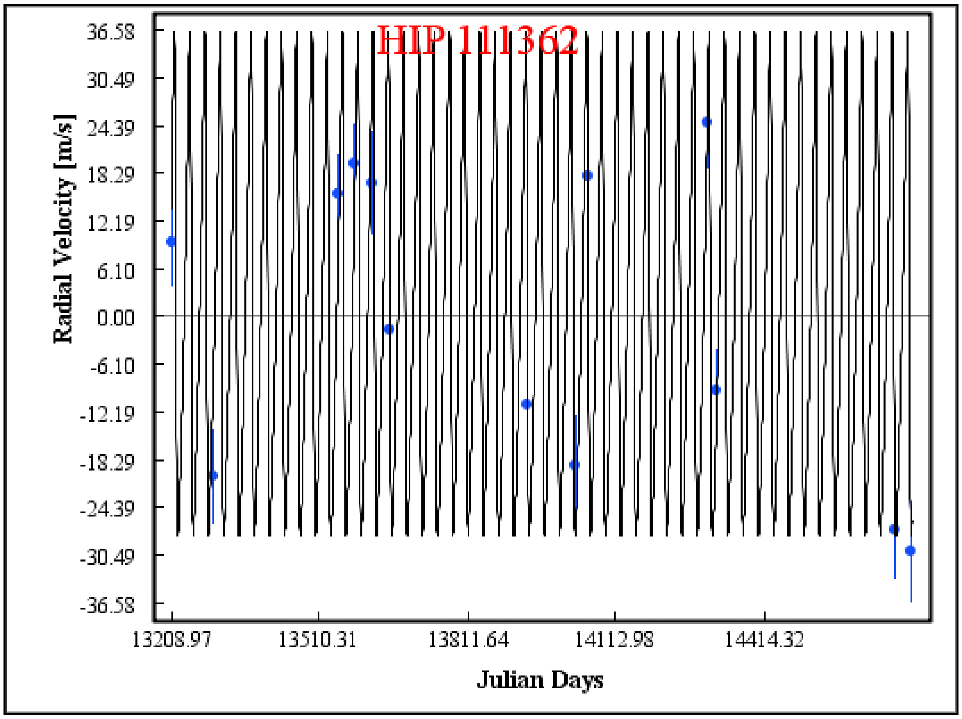

Figure 43. Radial Velocity vs. Julian Date - HIP 111362

Other Uninteresting

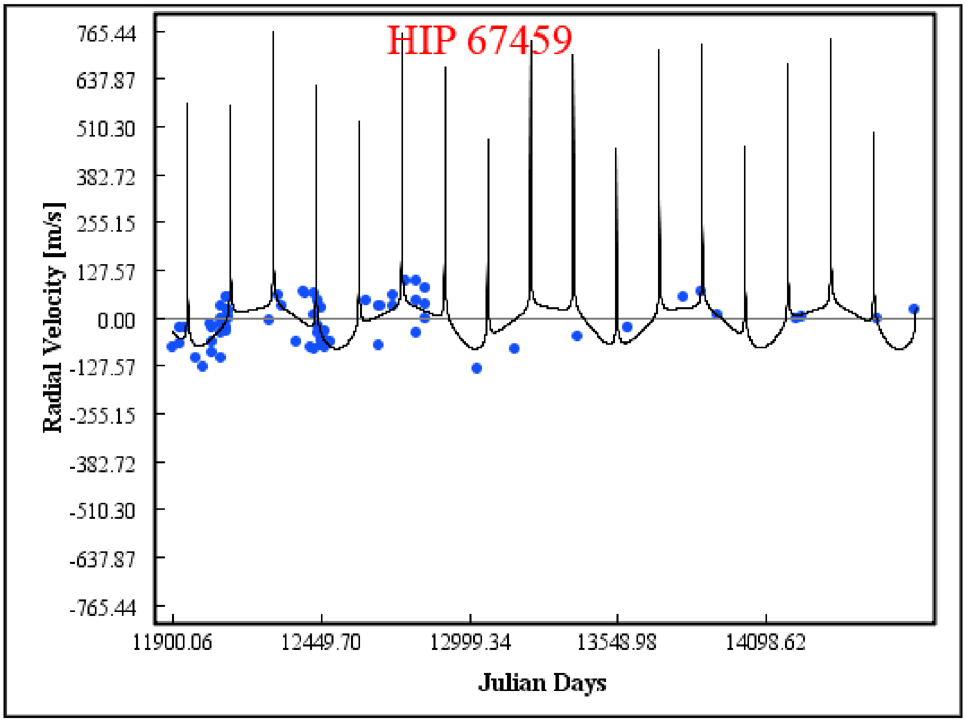

Figure 44. Radial Velocity vs. Julian Date - HIP 67459

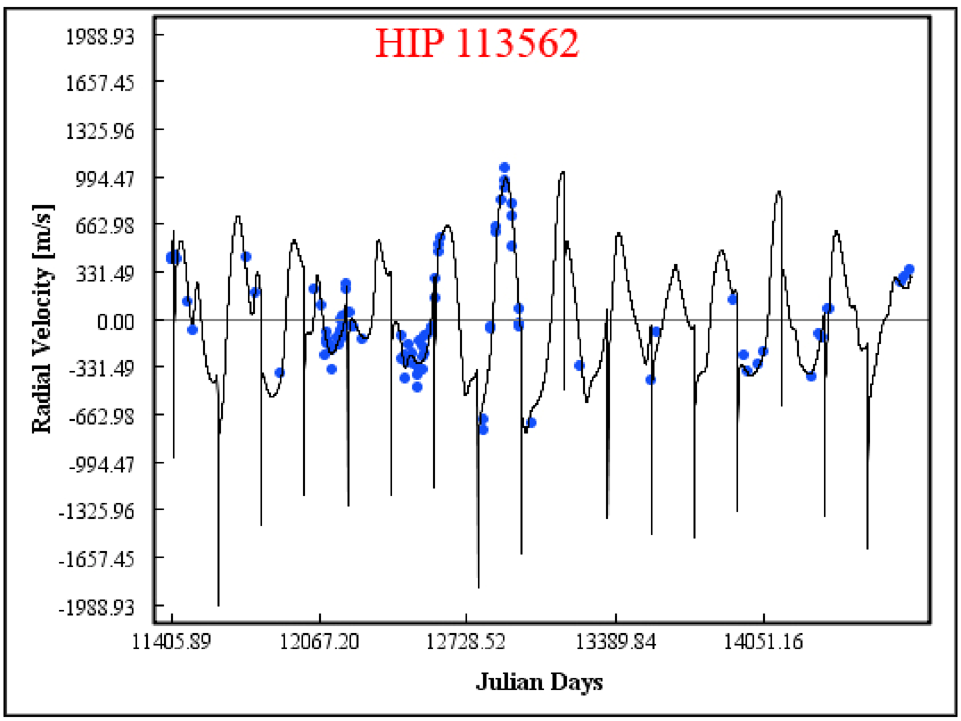

Figure 45. Radial Velocity vs. Julian Date - HIP 113562